Life cycle analysis of a community hydroelectric system in rural Thailand

May 2010

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Required for completion of
Masters of Science in Renewable Energy
School of Energy and Engineering, Murdoch University

Cover Photograph:
Andrew Pascale, Huai Kra Thing Village, Tak Province, Thailand. February 2006.

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Document Management:

Date	Version	Author	Description of Change
13/05/2010	2010-05-13	Andrew Pascale	Draft sent to supervisors and proof-reader
17/05/2010	2010-05-17	Andrew Pascale	Adjustments recommended by Tania Urmee
19/05/2010	2010-05-19	Andrew Pascale	Adjustments suggested by Mr. Connie Pascale
20/05/2010	2010-05-20	Andrew Pascale	Adjustments recommended by Andrew Moore
21/05/2010	2010-05-21	Andrew Pascale	Submitted to Murdoch University
27/09/2010	2010-09-21a	Andrew Pascale	Adjustments suggested by reviewers: Prof Philip Jennings and Mr. Adam McHugh
27/09/2010	2010-09-21b	Andrew Pascale	Adjustments reflecting feedback received from Andrew Moore, Tania Urmee, Barbara Nebel, Michael Faltenbacher, David Drysdale
24/10/2010	Final	Andrew Pascale	Submitted for Thesis Deposit to Murdoch University

Declaration

I declare that this thesis is my own research, except where other sources are fully acknowledged by footnotes or referencing. The thesis contains as its main content work which has not previously been submitted for a degree at any university.

Andrew Pascale

Abstract:

This study iteratively applies life cycle assessment (LCA) to a three kilowatt community hydroelectric system located in Huai Kra Thing (HKT) village in rural Thailand. The cradle to grave analysis models the hydropower scheme's construction, operation and end of life phases over a period of twenty years and includes all relevant equipment, materials and transportation. This study asks whether the HKT hydroelectric power system has the fewest environmental negatives of equivalent electrification options for the village over its 20 year life span.

The study results in the enumeration of the environmental credentials of the HKT hydropower system and highlights the need to place environmental performance, and LCA itself, in a proper context. Credentials are established though comparison with rural electrification alternatives and sensitivity analyses.

In the broadest sense, LCA results for the HKT hydropower system are in line with a common trend reported in hydropower LCA literature, namely that smaller hydropower systems have a greater environmental impact per kWh than larger systems. Placed within a rural electrification context, however, the HKT hydropower system yields better environmental outcomes than all surveyed alternatives. Sensitivity analyses reveal that only when worst system design and performance are approached do the environmental credentials of the HKT hydropower system become questionable.

Successful community electrification rests on the locally led adaptation of globally sourced technology to meet the specific environmental, social and economic challenges of rural areas. The further useful application of LCA to rural electrification in Thailand requires similar intervention. Local stakeholder involvement is needed to adapt LCA to rural electrification conditions, collect Thai specific manufacturing data, normalize results to Thailand and report

findings in an appropriate manner for local populations. Undertaken collaboratively with local stakeholders and integrated with tools such as life cycle costing, LCA can be an indispensable input into rural electrification decision making in Thailand.

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Acknowledgements

The author would like to thank and acknowledge the following people:

My advisers, Andrew Moore and Tania Urmee for giving me license to follow my passions and their continual feedback, advice, understanding and support. My partner Laurina Kersten for her patience, understanding and willingness to deal with my increasingly questionable sanity in the pursuit of this thesis. My family for unquestioning support and love that continues to cross oceans and provides the base for my being. My father for his invaluable ability to see to the heart of matters and convey their importance to even the most stubborn audience. The entire Border Green Energy Team (BGET) – Santi, M, Thai, Muang, Salinee and the many volunteers I have had the pleasure of working with over the years. KNCE, TBCAF and TOPS – with special thanks to Watit, Sam, Surat, Yo Ten, Dtay, Asiwene and Pong Pong for my local and cultural education. ZOA – with special thanks to Hans and the Dr. of Love and project foreman, Mr. Polchai for my Toquita education and the understanding that problems are not necessarily problems. Palang Thai – Chris, Chom and the kids for inspiration, advice, friendship and a couch to sleep on. Walt Ratterman for inspiration and example. The entire villages of Huai Kra Thing and Mor Ti Hta for teaching me far more than I ever taught them. Dr. Jonathan Whale and Dr. David Doepel for opportunities to expand my horizons, hone my skills and support myself. PE International for the use of the GaBi 4 software and database. Murdoch University and PE International reviewers for their time, guidance and suggestions.

This thesis is dedicated to my mother.

Acronyms

ADP	Abiotic Depletion
AP	Acidification Potential
BCS	battery charging systems
BGET	Border Green Energy Team
BUWAL	Bundesamt für Umwelt, Wald und Landschaft
CED	Cumulative Energy Demand
CML	Institute of Environmental Sciences, Universiteit Leiden
ELC	electronic load controller
ELCD	European Reference Life Cycle Data System
EOL	end of life
EPD	Environmental Product Declaration
EP	Eutrophication Potential
g	grams
GHG	greenhouse gas
GNESD	Global Network on Energy for Sustainable Development
GWP	global warming potential
HDPE	high-density polyethylene
IEA	International Energy Agency
I/O	Input/Output
IGC	Induction Generator Controller
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
ISO	International Organization for Standardization
KNCE	Karen Network for Culture and Environment
kg	kilograms (one thousand grams)
km	kilometres (one thousand metres)
kVA	kilovolt-ampere
kW	kilowatt (one thousand watts)
kWh	kilowatt hour

LCA	life cycle assessment or life cycle analysis
LCC	Life cycle costing
LCI	Life cycle inventory
LCIA	life cycle impact assessment
m	meter
MDG	Millennium Development Goals
msds	material safety data sheets
MW	megawatt (one thousand kilowatts)
NPC	Net Present Cost
ODP	Ozone Depletion Potential
PCA	process chain analysis
PAT	pump as turbine
PE	PE International
PEA	Provincial Electricity Authority
PED	Primary Energy Demand
POCP	Photochemical Ozone Creation Potential
PP	polypropylene
PVC	polyvinyl chloride
PWB	printed wiring board
RER	regional Europe
RNA	regional North America
SHS	solar home systems
SPI	Sale Price Indicator
THB	Thai Bhat
UNDP	United Nations Developing Programme
UNEP	United Nations Environment Programme
USD	United States Dollars
USLCI	United States Life Cycle Inventory
w, W	Watt

Glossary

Hydroelectric power system - system that converts the power in flowing pressurized water to electrical power.

Kilowatt hour (kWh) – a measure of energy. One kilowatt of power expended consistently over one hour. One kilowatt hour is 3.6 mega joules (another measure of energy).

Life cycle assessment or life cycle analysis (LCA) - an iterative process aimed at understanding the full range of environmental impacts associated with the life cycle of a particular product or service (ISO 1998).

Life cycle costing (LCC) - the calculation of a project's cost, in a specific currency and at a specific time, from inception to end of life. Costs are adjusted for anticipated inflation over the life time of the project and are discounted by a factor to account for the project's perception of the value of money over time and to place costs in a specified currency and time.

Life cycle inventory (LCI) data - details all of the inputs and outputs involved with a product or service occurring within a specified boundary. Examples of common inputs and outputs include energy, natural resources and pollutants.

Life cycle impact assessment (LCIA) - the process of classifying, converting and aggregating LCI data to express a set of categorized impact results. Each categorized impact is expressed using a reference unit. An example of an LCIA category is Global Warming Impact (GWP) which tracks pollutants aiding climate change and is expressed in grams of CO_2-equivalent.

Rural electrification – the provision of electricity to rural areas and rural peoples.

Sensitivity Analysis - Examines the relationship between key system inputs and the results reported in relevant studies. The systematic variation of individually inputs or groups of inputs coupled with observation of the resulting variations in overall results.

Watt (W), kilowatt (kW), megawatt (MW) – each is a measure of power. A kilowatt is 1000 watts. A kilowatt is 1.34 horsepower (another measure of power). A megawatt is 1000 kilowatts.

1. Introduction

In 2003 a UNDP report estimated that over two billion people lacked access to electricity. The same report found a fundamental link between the Millennium Development Goals (MDG) - which range “from halving extreme poverty to halting the spread of HIV/AIDS to enrolling all boys and girls everywhere in primary school by 2015” (UNDP 2003, v) - and the provision of energy services, especially in rural areas and developing countries. Required energy specific change was not limited to the need for “changes in energy consumption patterns in rich countries” but also highlighted “the use of low cost, low-emission technologies in developing countries”, (UNDP 2003, 126). One hundred and eighty nine countries adopted the MDGs in September 2000.

Rural electrification and the provision of low cost, low emission technology in developing countries require decision makers to be well informed on the costs, appropriateness and environmental credentials of all available options. While cost and appropriateness are often shaped by observable local considerations, environmental considerations are increasingly influenced by global concerns and are harder to fully determine and convey to all stakeholders.

Life Cycle Assessment (LCA) is an iterative method of exploring and improving understanding about the environmental impacts of a product or service system (ISO 1998). It has been used to explore the environmental impacts of various large scale electrification systems (IEA 2002). A literature survey suggests that LCA has yet to be fully utilized to inform discussion and decision making around smaller scale rural electrification systems. The few studies applying LCA to rural electrification in developing countries thus far have focused on solar home systems (Alsema 2000) and biodiesel (Gmünder et al. 2010).

This thesis aims to expand rural electrification literature, and further inform rural electrification decision makers, through a life cycle assessment of a hydro powered community electrification scheme in rural Thailand. To achieve this aim, GaBi software is used to model a three kilowatt (kW) hydroelectric power system located in Huai Kra Thing (HKT) village in Tak Province, Thailand.

Tak Province is one of 76 provinces in Thailand, features large swaths of rugged mountainous terrain and shares a border with Burma's Kayin State (Kawthoolei). Huai Kra Thing village consists of roughly 45 houses containing 230 men, women and children - the majority of which are ethnically Kayin. Agriculture is the main occupation of the villagers (KNCE 2007) although entrepreneurs offer a variety of services and goods. Villagers rely on animal husbandry and the wealth of the surrounding forest to meet their remaining subsistence need.

The village road system consists of a single central road allowing access to two churches, a medical clinic and a primary school. Water is available from a gravity feed water system connected to most household taps. Wood fires serve as the primary energy source for cooking and lighting for evening socializing. Lighting from fires has been supplemented over the years by candles and electricity. Through 2006, electricity was supplied by small diesel generators, a wide array of batteries, and government supplied solar home systems.

Constructed in early 2006 through the combined efforts of Thailand/Burma border organizations, local villagers, refugee camp students, school students from the USA and the United Nations Development Programme (Greacen 2006), the Huai Kra Thing hydroelectric system harnesses power from a nearby river to supply year round electricity to seven community buildings. System design followed a "soft approach" which minimizes large permanent structures and utilizes locally sourced and easily replaceable structures (Greacen 2004, 197).

As its central research question, this study asks whether the Huai Kra Thing 3kW hydroelectric power system has the fewest environmental negatives of equivalent electrification options for the village over a 20 year life span.

Specific goals of the study are to:

- quantify the environmental impacts of a community sized hydropower system in rural Thailand using a simplified and transparent LCA;
- compare hydropower LCA results with alternative electrification options for the community;
- detail specific means by which the environmental performance of similarly designed hydropower systems can be improved, and;
- explore the wider use of LCA in Thailand and other rural electrification efforts.

Results of the community hydroelectric system LCA are presented using the functional unit of one kilowatt hour (kWh) and compared with other electrification options across relevant life cycle impact assessment categories. Life cycle costing (LCC) is undertaken in this study's appendices to further inform the discussion of LCA results. Possible uses for the study include strategic rural electrification planning, eco-design of systems and the improvement of existing and planned remote hydropower systems. Potential audiences include academics, planners, environmentalists, engineers, villagers, community organizations and system equipment manufacturers and distributors.

Beyond application to rural electrification, this study also aims to expand hydropower LCA literature. Large systems dominate hydropower LCAs (Hondo 2005; Gagnon et al. 2002; Pehnt 2006; Vattenfall 2008; Rule et al. 2009; IEA 2002). The 300kW hydropower system analysed by Pehnt (2006) represents the only hydropower system in LCA literature with a capacity of less than one megawatt (MW, one thousand kW). Current LCA literature certainly does not cover hydropower systems in the 3kW capacity range. This is notable in that other renewable energy systems benefit from LCA literature covering grid tied 1kW solar PV systems (Moore 2009), a 400 watt (W) off-grid wind power system (Fleck & Huot 2009) a 7.5 kilovolt-ampere (kVA) generator running on 100% vegetable oil (Gmünder et al. 2010) and 49W and 24W solar home systems (Alsema 2000).

The lack of life cycle inventory (LCI) data for manufacturing processes in Thailand, and the resulting use of substitution and approximation in modelling Thai systems, represents the largest risks of limitation to the study. However, since comparisons can be made with other studies using similar methods, and well applied sensitivity analyses can explore critical issues even when models are imperfect, the risk of limitation to the study is low to moderate. At the very least, this study creates a base from which further iterations and explorations of rural electrification using hydropower in Thailand can be launched.

This report reads as follows. Chapter two introduces and details life cycle assessment. Chapter three provides a quick methodology overview. Chapter four lays out the framework for the community hydropower LCA. Chapter five describes the Huai Kra Thing hydroelectric system and alternative rural electrification models. Chapter six presents and compares the results of LCA modelling. Chapter seven undertakes sensitivity analyses on key scheme characteristics. Chapter eight interprets and discusses the research results as well as details study limitations. Chapter nine presents a conclusion and makes recommendations for further study and the application of results.

2. Life Cycle Assessment (LCA)

Life cycle assessment is an iterative process aimed at understanding the full range of environmental impacts associated with the life cycle of a particular product or service (International Standardization Organization 1998).

2.1 ISO standards and framework

The International Organization for Standardization (ISO) provides a set of standards aimed at guiding LCA practice. ISO 14040 describes the basic LCA framework displayed in Figure 2.1. ISO 14040 also details LCA principles. ISO 14044 covers the definition of goal and scope, life cycle inventory assessment, life cycle impact analysis, LCA interpretation and LCA reporting (ISO 2010).

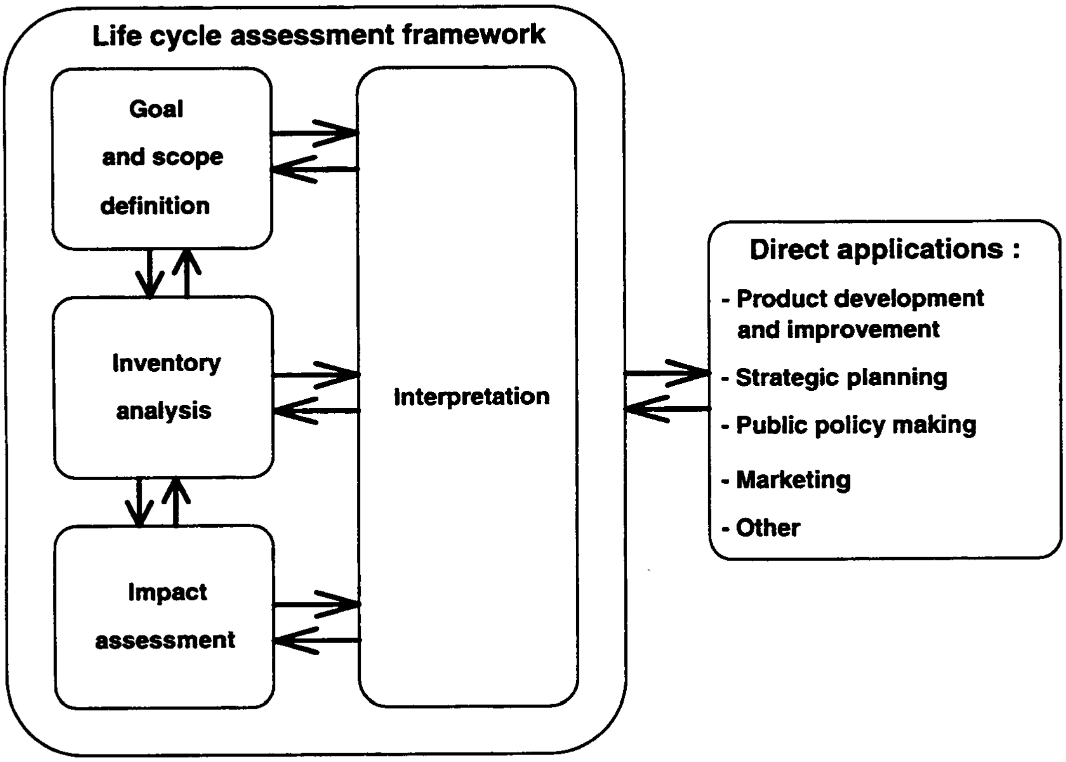

Figure 2.1 LCA framework (ISO 1998, 4)

2.2 LCA process

ISO 14040 states that

"LCA is a technique for assessing the environmental aspects and potential impacts associated with a product, by

- compiling an inventory of relevant inputs and outputs of the product system;

- evaluating the potential environmental impacts associated with the inputs and outputs;
- interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study."

(ISO 1998)

LCA process iterations occur as required and allowed by the study's scope and goals, the availability of data, and limitations on time, manpower and money. Conducting the entire process using recognized standards in a transparent, diligent and fully documented manner aids an LCA in meeting its intended application – its purpose - as well as retaining credibility for continued modification, improvement and use.

2.3 Definition of Goal and Scope

The LCA of a product or service considers all resource flows, geography covered, technology employed, operating procedures, pollutant and waste flows, product/service production flows, transportation required, product/service consumption flows, product/service lifetimes, disposal flows and methods of resource recapture. The purpose of the LCA then determines:

- the appropriateness of including or excluding each prior consideration;
- the setting of boundaries within which to undertake the LCA;
- the making of assumptions which will guide the LCA process, and;
- the environmental impacts that should be focused on (ISO 1998).

2.4 Life cycle inventory analysis

With goal and scope in hand, life cycle inventory (LCI) data is then gathered for all considerations deemed inside the LCA's scope and boundaries. LCI data details all of the inputs and outputs involved with a product or service occurring within a specified boundary. Examples of common inputs and outputs include energy, natural resources and pollutants (Guinee (ed) et al. 2001).

2.5 Life cycle impact analysis (LCIA)

LCIA is the process of classifying, converting and aggregating LCI data to express a set of categorized impact results. Each categorized impact is expressed using a reference unit. Many classification and characterization methods, such as the CML 2001 Method (GaBi 4 2006), are recognized and in use. New methods are also created when required to meet novel or unmet goals of an intended application.

Characterization methods are concerned with general broad areas of protection including, "human health, natural resources, the natural environment and the man-made environment" (Guinee (ed) et al. 2001, 142). Common protection area characterization factors tracking the impact of substances released into the environment focus on:

- Global Warming Potential (GWP) – pollutants aiding climate change. Guinee et al. (2001) suggest a factor time horizon of 100 years.
- Acidification Potential (AP) – pollutants causing acidification of the environment.
- Eutrophication Potential (EP) – pollutants increasing environmental nutrient levels.
- Ozone Layer Depletion Potential (ODP) – increased terrestrial radiation due to pollutants causing thinning of the stratospheric ozone layer.
- Photochemical Ozone Creation Potential (POCP)– airborne pollutants creating ozone through interaction with sunlight (Guinee (ed) et al. 2001).

Common protection area characterization factors dealing with resource use include:

- Abiotic Depletion (AD) – depletion of non-living resources.
- Primary Energy Demand (PED) – total consumption of renewable and non renewable energy resources by a product/system (GaBi 4 2006).

A life cycle impact assessment (LCIA) is presented using a functional unit intended to best match the impact results to the intended application. LCIA results can optionally be packaged for communication and comprehension in a number of ways – usually involving the normalization and weighting of results (GaBi 4 2006).

2.5 Interpretation and sensitivity analysis

Interpretation occurs throughout the entire process, often providing feedback into the system which shapes future iterations. LCA processes and results are complex. Interpretation is often aided by sensitivity analyses which allow LCAs to explore results even when hindered by assumptions and data limitations.

Sensitivity analyses examine the relationships between key system inputs and the results reported in relevant studies. They do so by systematically varying individually inputs or groups of inputs while simultaneously observing the variation in overall results. For example, a simplistic sensitivity analysis on the relationship between petrol price and the various modes of commutation - bus, car, train, bicycle - would involve systematic variation in petrol price over a chosen range, coupled with close observation of the daily transport choice made by commuters. Low petrol prices are likely to correlate with single vehicle commuting. High prices will likely promote bus and train patronage.

2.6 Application

LCA is not intended to be the decision making process but rather is intended to be a transparent input into a decision making processes. LCA is used across a broad spectrum of end users.

A Swedish power company uses LCA in order to assess the environmental impact of their hydropower operations in Nordic countries (Vattenfall 2008) and as a product marketing tool (EPD n.d.). An Australian steel maker uses LCA to "improve both steelmaking processes and products" (BlueScope Steel Limited n.d.). A dairy farm in the USA uses LCA in order to "identify sustainability farming practices" (Birnie 2010). An international NGO recently used LCA in order to make more informed rural electrification decisions (Gmünder et al. 2010).

Diverse LCA application supports a broad range of decision making processes.

3. Methodology

As its core process, this study pursues the LCA modelling of a community sized hydroelectric system in rural Thailand. Figure 3.1 details this study's approach to the hydropower scheme LCA.

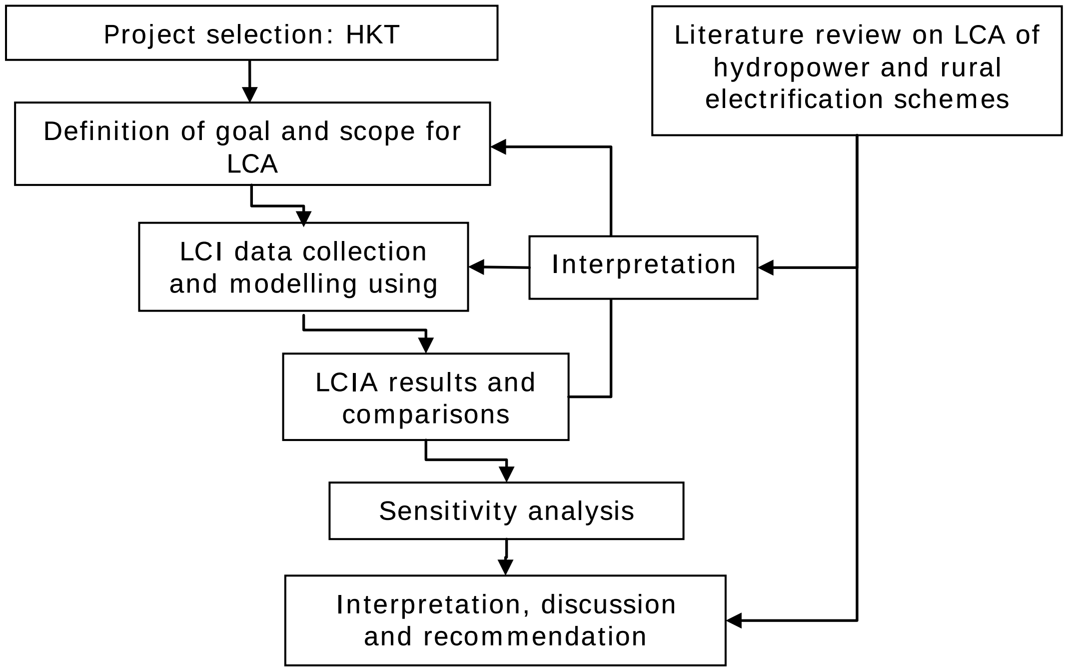

Figure 3.1 Core study process

3.1 Project and software selection

The 3kW Huai Kra Thing (HKT) hydropower system was chosen due to availability of literature from the Border Green Energy Team (BGET) website and the author's own familiarity with the project. The author was a central part of project management for the 2006 installation. GaBi 4 software was chosen due to the availability of software and advisor familiarity with the software package.

3.2 LCA process

LCA modelling and impact assessment on the project followed in an iterative process:

- life cycle inventory data collection on HKT hydropower scheme,
- data and process entry into GaBi 4 educational LCA software and

- life cycle impact analysis and comparison of results with alternative options.

After the presentation of the final iteration's LCIA results, sensitivity analyses are performed to further inform results and pursue important topics. A discussion of the results and sensitivity analysis ensues with reference to existing literature on hydropower and rural electrification LCAs. Achievement of research goals by the study is assessed. Conclusions are made. Recommendations follow.

3.3 LCA reporting

LCA reporting guidelines are drawn from ISO standards, best practice LCA examples such as the *Life Cycle Assessment (LCA) of a 1kWp Photovoltaic System Installed in Australia* (Moore 2009) and industry standard environmental declaration systems such as the Environmental Product Declaration® system (EPD n.d.). Thorough and transparent reporting on this study aims to allow thoughtful comparison to LCAs undertaken on schemes with any number of matching characteristics.

4. Goal and Scope of LCA

4.1 Purpose of study

The environmental benefits of community sized hydropower are referred to as a justification for its implementation in rural areas (Blanco et al. 2008; Pereira et al. 2010; Greacen 2004; Khennas et al. 2000). However, the full environmental impacts of community sized hydropower schemes are not quantified in literature. To address this information gap, this study will thoroughly assess the cradle to grave environmental impacts of the Huai Kra Thing village hydroelectric scheme implemented in rural Thailand.

4.2 Intended application

The application of LCA to rural electrification is aimed at further informing discussions on the environmental impacts of the spread of electricity to rural areas of Thailand. Understanding the factors that influence the life cycle environmental performance of the HKT hydroelectric systems provides the opportunity to improve overall system sustainability and bring focus to the distribution of manpower and funding by rural electrification decision makers. Possible uses for the study include strategic rural electrification planning, eco-design of systems and the improvement of existing and planned remote hydropower systems.

4.3 Target audience

Initially, this study is intended for internal circulation at Murdoch University. Potential wider audiences include planners, environmentalists, engineers, villagers, community organizations and system equipment manufacturers and distributors.

4.4 Product System

The following subsections describe the characteristics of the system under study and shape the form and output of this LCA.

4.4a System function and allocation of impacts

The sole function of the HKT hydroelectric system considered in this report is the generation of electricity. Neither the co-production of additional forms of energy (such as the use of dump load heat energy to do work) nor the potential use of any section of the hydropower scheme for irrigation, aquaculture or recreation is considered in this study. Furthermore, as the HKT hydroelectric system is the only hydropower system in this stretch of the river and the only community electrification scheme with a distribution grid in HKT, 100% of this study's calculated impacts are allocated to the HKT hydroelectric system.

4.4b Scheme component inclusion and exclusion

This LCA models the HKT scheme as it was installed in early 2006. While the model covers the provision of an electrification infrastructure in HKT village, house wiring and core energy services are excluded from the study. This exclusion mirrors previous hydropower LCAs, but fails to acknowledge the special circumstances of rural electrification projects which are focused on and include the complete provision of core energy services, such as lighting, for end users (Khennas et al. 2000; Alsema 2000). Time limitation rather than appropriateness was the central driver in this decision.

4.4c Inclusion of backup power

Gagnon et al. (2002) point out that the quality and annual availability of the power produced by an electricity generating system are not always adequately addressed in LCAs. As a means to adjust for intermittency or annual availability issues they advise that the LCA of an intermittent or seasonally fluctuating scheme should include all backup power sources required to maintain a minimum level of service. The HKT installation was designed to provide year round, uninterrupted power for community buildings. Villagers have access to distributed backup power in the form of government provided solar home systems. A backup power system is not included in the model.

4.4d Functional unit, energy availability, system losses

The functional unit for this study is one kWh of electrical energy. One kWh of electrical energy is a common functional unit in LCA studies on electrical power generation (IEA 2002). However studies vary in where that one kWh is measured and whether the functional unit includes consideration of system losses.

This functional unit used in this LCA represents one kWh of electrical energy available for consumption by the villagers at point of connection to community structures. The functional unit does not concern itself with how energy is used by villagers, only that the energy is available to them. All system losses incurred after generation by the turbine (transmission, distribution and electrical conditioning) are included in functional unit accounting.

4.4e System availability

Anecdotal reports from villagers and BGET technicians suggest considerable downtime for HKT and other regionally located and similarly sized and constructed hydropower installations. In light of such feedback, the turbine is assumed to be operational at a power output of 1.6kW for a conservative 85% of the year.

4.4f Considerations of system and component lifetimes

This study models the HKT system over a 20 year span. This seems reasonable due to the wide variation in system component life spans and eases discussion of rural electrification alternatives such a solar PV (Kenfack et al. 2009; Alsema 2000) and wind (Varun et al. 2009). The life spans of HKT system components are estimated using personal observation of HKT installation methods, a literature survey, and anecdotal reports from technicians employed by BGET.

All components lasting less than the 20 year lifespan are replaced as many times as necessary over the span. Due to considerable uncertainty around long term component longevity in the HKT installation, any component with a potential life span of greater than 20 years is limited to a 20 year life span.

4.4g Renewable local resources

Scheme components sourced from local organic renewable resources are marked for replacement every two to five years. However, while locally sourced wood[1] and bamboo[2] used for construction purposes are included in the model, impacts from their use have not been included. Local organic renewable resources are treated as having a zero net impact cycle if they:

- do not leave their regional ecosystem;
- are not treated with a preservative;
- are harvested and transported using 100% human power, and;
- are allowed to decompose in situ after use.

Consider the example of a locally harvested tree used as a transmission pole. With respect to global warming potential (GWP), the wooden pole is expected to be a CO_2 sink during its growth phase and then to fully release the same amount of CO_2 during its harvest, use and decomposition. While this is an oversimplification, impact leakages from local resources that are used in a sustainable manner are expected to make up less than 1% of total system environmental impacts and are ignored.

4.4h Non-Renewable local resources

Scheme components sourced from local non-renewable resources include rocks, gravel and sand. For modelling purposes, rocks and gravel are treated as the same item. All locally sourced non-renewable materials that do not leave the regional ecosystem and are collected and transported using 100% human power are considered to have zero net impact in this LCA.

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[1] Using estimated volumes and an assumed density.
[2] Using estimated masses.

4.4i Human labour and maintenance

Human labour, which accounts for 100% of the power used during system installation, is outside the scope of this LCA. Likewise, while materials and transportation for equipment replacement are included in the model, human labour needed for maintenance and replacement is not.

4.4j Packaging, paints and lubricants

Packaging is used to facilitate the sale and transport of equipment safely from purchase to installation. However, this LCA does not include packaging material in the modelling of system components. Packaging materials are expected to make up less than 1% of total system environmental impacts and are ignored. Paints and lubricants used on system equipment such as the turbine are also expected to make up less than 1% of total system environmental impacts and are ignored.

4.4k End of Life: Disposal, recycling and re-use

During the end of life phase all system equipment is disposed of in the easiest manner possible. On replacement, each now redundant item is stockpiled locally until a time when another use might be found for it or villagers might gain some benefit (ex. a recycling scheme) from disposing of it regionally. Given this context, neither re-use of system materials nor recycling is included in the LCA model.

4.4l Water Consumption

While a UNESCO-IHE Institute for Water Education report associates water use from hydropower mainly with water evaporation and seepage from large reservoirs (Gerbens-Leenes *et al.* 2008), the OECD states explicitly that “Water used for hydroelectricity generation is an in situ use and is excluded” (OECD 2009, 186). Due to a minimal reservoir size and the return of water used for power generation to the river, water flowing through the system during operation is not tracked in this study. However, water consumed in the production of all scheme equipment and materials is included in this LCA.

4.4m Land Use

Land use is tracked in this LCA. However, aside from noting the area affected and what type of land use change occurred, ex. “Forest to building”, no land use change categories are assigned in software modelling.

4.4n Waste Heat

Locally produced waste heat sent to air is tracked in the LCA but treated as having a negligible impact on both climate change and local ecosystems. Waste heat sent to water is tracked and recognized as having a larger potential impact on local ecosystems (Guinee (ed) et al. 2001).

4.5 System Boundaries

The following cradle to grave analysis tracks the extraction and processing of resources to the make products and materials comprising the HKT hydropower system. Materials and equipment are then followed through the use phase and beyond to their end of life phase. Local disposal is considered. Regional disposal, recycling and reuse is not. Transportation of all equipment from point of manufacture to HKT is included in the model. Emissions from all modelled processes are tracked, as are the resources flowing across the system boundary. Figure 4.1 presents a diagram showing included processes and system boundaries.

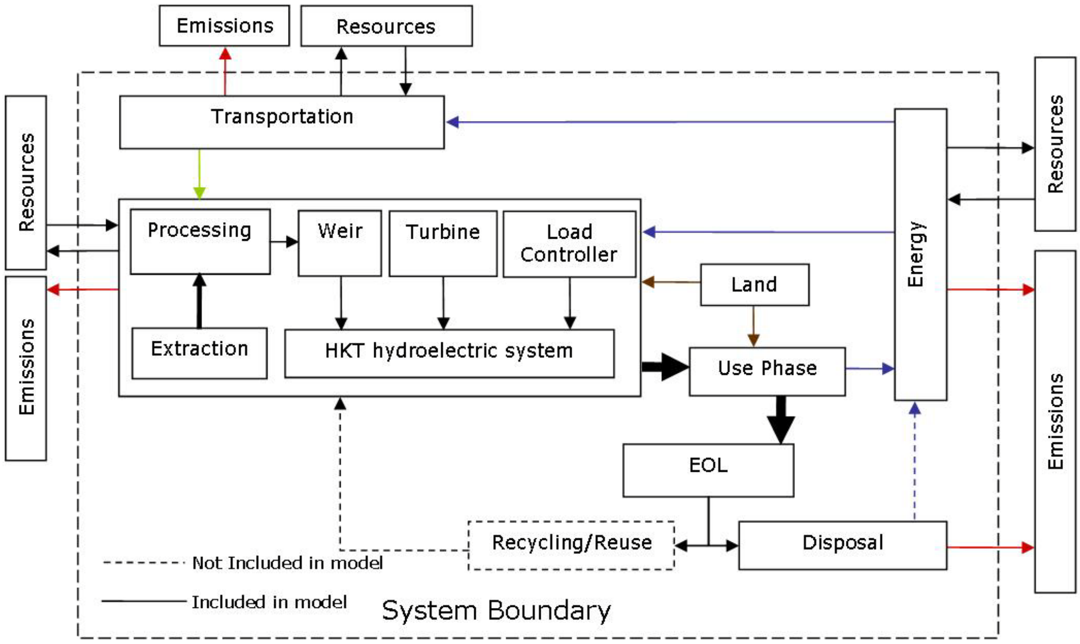

Figure 4.1 Simplified system process drawing showing scope and system boundaries

4.6 Life cycle inventory exclusion cut-off criteria

The HKT hydroelectric system is comprised of multiple product systems. Product systems are themselves made up of many unit processes. ISO 14041 (1999) recognizes that LCA is an iterative process and that inclusion of all inputs, outputs and processes in an LCA requires a substantial time commitment and may not be practical. When complete modelling is impractical cut-off criteria are established. Cut-off criteria provide a rough guide for the thoroughness of the LCA and detail not only what is included in the LCA, but equally as important, estimate what is not (Guinee (ed) et al. 2001).

This LCA aims to account for at least 95% of the total mass and 90% of the total energy inputs of the HKT hydropower scheme. All individual mass flows comprising more than 1% of total mass flows are to be included. Excluding the calorific content of scheme materials, all individual energy flows above 2% of the total energy input are included. If an individual mass or energy input flow is below cut off criteria, but is expected to have environmental relevance, it is also included in the LCA. Cut off criteria for this study are based on ISO 14041 suggestions for mass, energy and environmental relevance (ISO 1999).

4.7 Assumptions and limitations

LCA modelling of the HKT hydropower scheme required a tiered system of transparent assumptions in order to create a useful end product. Figure 4.2 presents the tiered assumptions made in the modelling of the HKT hydropower system and qualitatively assesses each assumption's potential impact on results and its risk of limitation on the study. Subsequent subsections detail the guidelines and methods used to arrive at each tier.

Usefulness of LCA and LCIA results

Transportation Assumptions
Potential impact on results: low. Risk of limitation on study: low.

Assumptions surrounding the use of substitute, approximated and dummy processes
Potential impact on results: high. Risk of limitation on study: medium.

Assumptions on the quality of GaBi 4 software and databases
Potential impact on results: high. Risk of limitation on study: low.

Assumptions made due to the availability of LCI data
Potential impact on results: high. Risk of limitation on study: medium.

Assumptions involving project documentation and veracity of estimations
Potential impact on results: low. Risk of limitation on study: low.

Figure 4.2 Major assumptions and limitations shown in a tiered relationship along with qualitative potential impact and risk summary (low, medium, high)

4.7a Assumptions involving project documentation and estimations

Detailed accounting of materials installed as part of the project does not exist.[3] The following guidelines were used in recreating the material list used for the HKT hydropower scheme:

- If documentation is available[3], the documentation is assumed to be accurate and all materials listed as part of the project are assumed to have been used in the installation.
- If documentation is not available[3], author estimations of resource and component quantities are made. The author's active role in the installation is assumed to allow for reasonably accurate estimations.

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[3] In English. Documentation in Thai is more detailed. The author's inability to read Thai is a limitation.

The potential impact on results is considered low, as is any risk of limitation on the study.

4.7b Assumptions made due to the availability of LCI data

ISO 14041 (1999) states that data used to model system flows should be temporally, geographically and technologically appropriate. LCI data for manufacturing processes in Thailand is not available[3] and the collection of LCI data for Thailand specific manufacturing practices is outside the scope of this study. Data available for free and in GaBi databases is fairly recent, but focuses on European and North American processes and the technologies used in those regions. However, as much of the available data represents industry standard processes and Thailand has a strong commitment to international industrial standards (TISI n.d.), this is not expected to be a major issue.

All processes used in modelling the HKT hydropower scheme involve substitution and approximation. All substitute and approximate processes chosen to model scheme components are assumed to be reasonable approximations of components found in the HKT system. Table 4.1 describes the source, geographical and temporal bias of GaBi 4 data used in this LCA. The technologies and countries represented by specific GaBi database processes can be found in GaBi database documentation.

Table 4.1 Source, geographical and temporal bias of data used in this LCA (GaBi 4 2006)

Source	Countries	Reference Year
BUWAL[4]	Switzerland (CH), Germany (DE), RER[5]	1996
PE International (PE)	DE, Global (GLO), United States (US)	2000-2005
ELCD[6]/PlasticsEurope	RER	2005
ELCD/PE	GLO[7]	2003-2005
USLCI[8]/PE	Regional North America (RNA), US	2003-2009

[4] Bundesamt für Umwelt, Wald und Landschaft (BUWAL)
[5] Regional Europe (RER)
[6] European Reference Life Cycle Data System (ELCD)
[7] Global (GLO)
[8] United States Life Cycle Inventory (USLCI)

The lack of LCI data specific to Thailand and its production technologies has a high potential to impact study results. Temporal bias of data has a low potential. As it is expected that this study will be compared with rural electrification LCAs limited by similar conditions, this is not seen as a severe limitation on the study. Furthermore, as LCA is an iterative process, this study creates a base from which further iterations can be launched.

4.7c Assumptions about the quality of GaBi 4 software and databases

Supplied GaBi 4 databases and software are assumed to be of high quality and to accurately report the impacts of a modelled process. High profile international usage (Geibig & Socolof 2005) of GaBi along with extensive website documentation supports these assumptions (GaBi 4 2006). Although the quality of the data used in an LCA model has a high potential to impact results, this study's use of the well supported GaBi package poses a low risk of a data quality limitation on this study.

4.7d Assumptions surrounding the use of substitute, approximated and dummy processes

LCI data limitations require that substitute and approximate processes be chosen/created to represent the manufacture of products and materials used in the HKT hydropower scheme. The method and assumption used to select and/or create substitute processes for a product is detailed in Figure 4.3 along with the risks of limitation for each step.

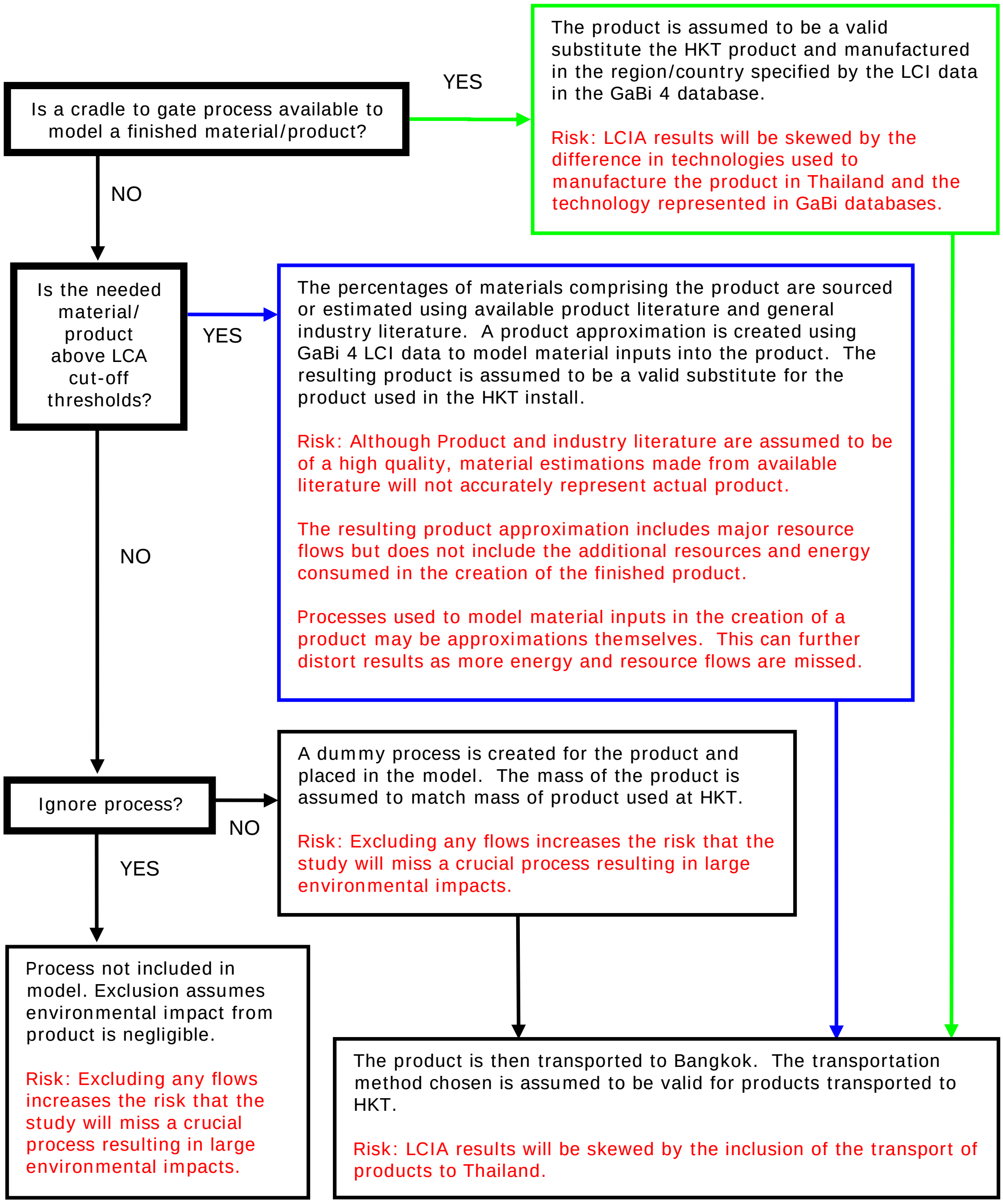

Figure 4.3 Flowchart detailing risks in the creation of substitute, approximate and dummy processes

The potential of substitute and approximated processes to impact study results is high. However, the risk of a major limitation on the study is only moderate as comparisons can be made with other studies using similar methods and well applied sensitivity analyses can explore critical issues even when imperfect models are used.

4.7e Transportation Assumptions

This LCA uses global, European, and North American LCI data to model transport modes and transport fuels in all countries spanned by the HKT hydropower scheme's life cycle. This substitution is assumed to be accurate enough to meet this study's scope. This study also assumes that Google Maps and the other internet sources providing the transportation distances and routes listed in subsection 5.9 are accurate enough to meet the scope of this LCA.

Transportation assumptions have a low potential impact on results and low risk of limitation on the study. A sensitivity analysis in Chapter 7 explores this assumption.

4.8 Selection of LCIA impact categories and indicators

The LCIA undertaken in this study reports on the base set of impact categories and indicators listed in Table 4.2. Selected categories are described briefly in Chapter 2. In this study, primary energy demand is the total amount of life cycle energy consumed by the scheme over its 20 year life span. LCIA results are scaled to the lifetime energy production in kWh calculated in subsection 5.12 and presented pre kWh for each LCIA category.

Table 4.2 LCIA categories addressed in this study

Life Cycle Impact Assessment Categories	Unit	Acronym
CML 2001 – Dec. 07, Global Warming Potential (100 years)	kg CO_2 -e	GWP
CML 2001 – Dec. 07, Acidification Potential	kg SO_2 -e	AP
CML 2001 – Dec. 07, Eutrophication Potential	kg PO_4 -e	EP
CML 2001 – Dec. 07, Ozone Layer Depletion Potential (steady state)	kg R11 -e	ODP
CML 2001 – Dec. 07, Photochemical Ozone Creation Potential	kg ethane -e	POCP
CML 2001 – Dec. 07, Abiotic Depletion	kg Sb-e	ADP
Life Cycle Impact Assessment Indicators	**Unit**	**Acronym**
Primary energy demand (net cal. value)	kWh / kWh	PED

4.8a Land use change

Land use change is not a formal part of LCIA results. However, the area of land occupied and type of land use change associated with occupation are detailed in the Chapter 5 description of the models and presented in Chapter 6 results.

4.9 Critical Review

Given the initial target audience of the study, no critical review is required. Should this LCA be presented to a wider audience, a critical review will be needed.

5. Description of LCA Models

This chapter provides a quick description of Huai Kra Thing village and then describes the models built for this LCA. The hydroelectric power system model is described in subsections 5.2 – 5.12. Alternative electrification models for the village are described in subsections 5.13 and 5.14.

5.1 Huai Kra Thing village

Huai Kra Thing village is located in Tak Province, Thailand. The village centre consists of roughly 45 houses containing 230 men, women and children. The village is home to two churches, a medical clinic and a primary school. Agriculture is the main occupation of the villagers (KNCE 2007). Government supplied solar home systems provide villagers with limited electricity. Appendix A provides a more detailed description of the village.

5.2 Hydropower scheme overview

The hydroelectric power system installed at Huai Kra Thing in early 2006 is a 3kW capacity, run of the river system.[9] The system was designed for year round electrification of seven community oriented buildings. System design followed a "soft approach" which minimizes large permanent structures and utilizes locally sourced and easily replaceable structures (Greacen 2004, 197). Figure 5.1 provides a basic overview of the community hydroelectric system and has separated the scheme into seven distinct physical sections.

[9] The installation is not described in this section but a brief description can be found in Greacen (2006). More in depth but generic description of community hydropower installs can be found either in physical book form (Inversin 1986) or online (Maher & Smith 2001).

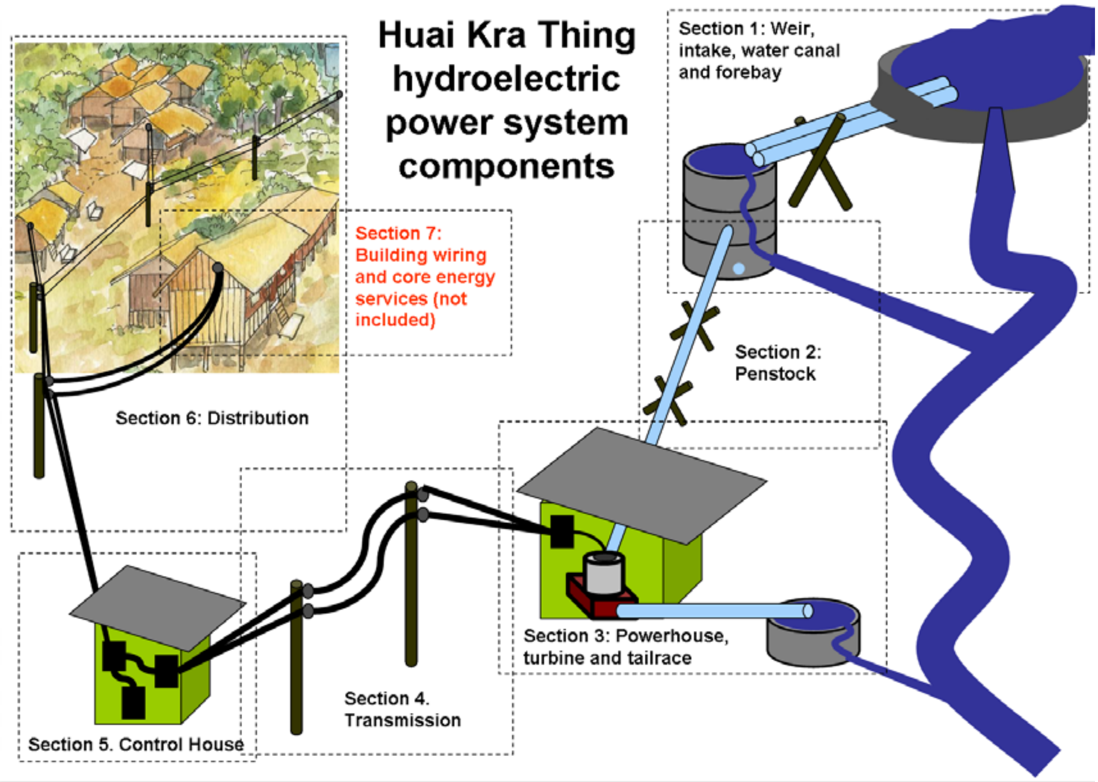

Figure 5.1 Overview of HKT community hydroelectric system with separation into physical sections. Karen village painting (Sein Sein Lin 2006).

5.2a GaBi 4 model overview

The HKT hydropower model and all GaBi 4 models created for this study are organized using nested process plans and global system parameters. A master plan for the HKT hydropower model describes the relationship between scheme sections and contains a nested plan for each section. Section plans contain additional nested plans describing component materials and products. Material and product plans may appear in multiple section plans.

The master plan for the GaBi 4 model of the HKT hydroelectric scheme can be found in Figure D-1 of Appendix D. Appendix B provides a high level overview of the state of the LCA model of the HKT hydropower scheme. The model has been created so that LCI data for Thai products and processes representing Thai manufacturing technology can be updated when such data becomes available. System parameters used in modelling the HKT system can be found in Appendix K.

5.3 Section 1: Weir, intake, canal and settling tank (forebay)

The goal of this portion of the hydroelectric system, pictured in Figure 5.2, is to provide a steady and clean flow of water to the penstock. Each individual component in this section has a specific role in achieving that goal. The weir's function is to resist the flow of water in the stream enough to keep the intake to the canal submerged while also allowing floating debris to pass over the structure. Located just behind the weir, the intake allows water to enter the canal and uses a filter to limit the size of debris entering the canal. The canal transports water to the settling tank – which is more generally called a forebay. The settling tank aims to keep the penstock full while allowing any remaining debris in the water to settle to the bottom of the tank.

Figure 5.2 Photos of weir and intake (left), canal (right) and settling tank (centre) as installed in HKT

5.3a Process overview and construction materials

Figure 5.3 below shows a process overview for this section of the HKT hydroelectric system.

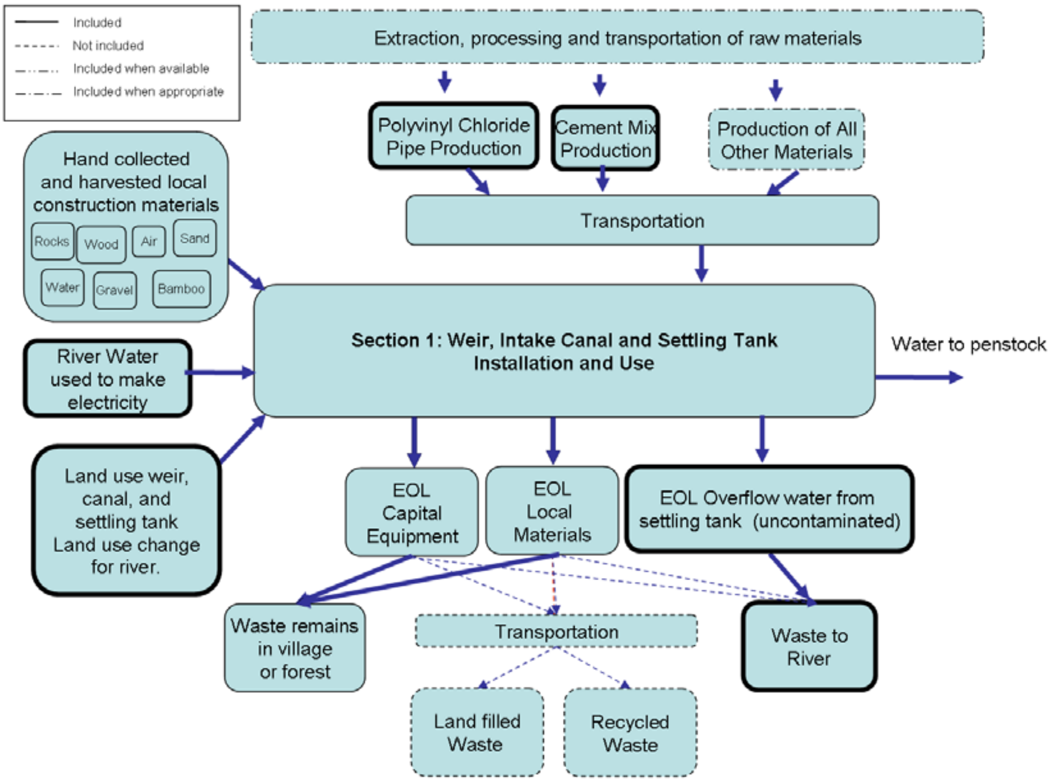

Figure 5.3 Process overview for weir, intake, canal and settling tank

Table 5.1 shows the material and land inputs used in modelling this section of the system. GaBi 4 process plans along with additional sub-plans for processes for this section can be found starting with Figure D-2 in Appendix D.

Table 5.1 20 year life cycle materials inputs for weir, intake, canal and settling tank

Item	Quantity	Unit	HKT Total Mass (kg)
Bags of dry cement mix for intake	0.67	bags	33.33
Bags of dry cement mix for settling tank	2.00	bags	100.00
Schedule 40 - 4" inch blue PVC pipe for canal	50.00	m	149.56
Schedule 40 - 1" blue PVC pipe cleanout valve	1.00	pce	0.05
Concrete rings for settling tank (made off site-purchased whole)	3.00	pce	150.00
Galvanized nails for fastening canal supports	60.00	pce	0.70
HDPE tarp used as stream bed liner at weir	8.00	sqm	6.22
PVC glue/solvent for canal	1.00	can	1.00
Bailing wire to tie plastic mesh filter to bamboo structure	12.00	m	0.07
Bailing wire to tie mesh filter and to tie canal to stands	92.00	m	0.56
50kg woven PP rice bags (purchased not reused) to hold rocks and sand for weir	133.33	pce	0.01
Plastic mesh filter (1cm^2) used to filter debris at intake	1.33	sqm	0.00
Plastic mesh filter (1cm^2) used to filter debris in settling tank	1.33	sqm	0.00
Local wood support structure for canal	20.00	pce	1585.53
Gravel Mixers added to dry cement to make wet concrete for weir/intake	64.34	kg	64.34
Locally collected rocks for weir	1666.67	kg	1666.67
Gravel Mixers added to dry cement to make wet concrete for settling tank	193.02	kg	193.02
Sand Mixers added to dry cement to make wet concrete for weir/intake	33.86	kg	33.86
Locally collected sand for weir	1666.67	kg	1666.67
Sand Mixers added to dry cement to make wet concrete for settling tank	101.59	kg	101.59
Water and Air Mixers added to dry cement to make wet concrete for weir/intake	5.30	kg	5.30
Water and Air Mixers added to dry cement to make wet concrete for settling tank	15.89	kg	15.89
Bamboo twist ties for weir	133.33	pce	0.67
Woven bamboo filter structure for intake	5.00	kg	5.00
Woven bamboo filter structure for settling tank	5.00	kg	5.00
Forest and river to weir and reservoir	25.00	sqm	
Forest to canal	6.35	sqm	
Forest to settling tank	0.50	sqm	
Reduced flow in river between intake and settling tank	70.00	sqm	

5.3b Production phase

Due to time and resource limitations, the production of all scheme equipment and materials can not be detailed. Each hydropower scheme section will only detail the production of the materials and equipment with the most relevance - that contribute the greatest environmental impact - to the section. The central production processes of interest in this section are for polyvinyl chloride (PVC) pipe and dry cement mix.

5.3b.1 Polyvinyl Chloride (PVC) Pipe Production process

The life cycle inventory (LCI) data for PVC pipe in the GaBi database is provided by PlasticsEurope. The data is cradle to gate, considered of good quality, applies to regional Europe (RER) and is from 2005.

PlasticsEurope LCI data for PVC pipe production models the extrusion of PVC pipe from suspension PVC. Suspension PVC arises from the polymerization of vinyl chloride monomer (VCM). VCM is the result of the oxychlorination of ethylene dichloride (EDC) (GaBi 4 2006). EDC is the product of chlorine and ethylene, which themselves arise as a by product of industries upstream from the PVC industry. Figure 5.4 provides a possible industry pathway for the production of ethylene and chlorine.

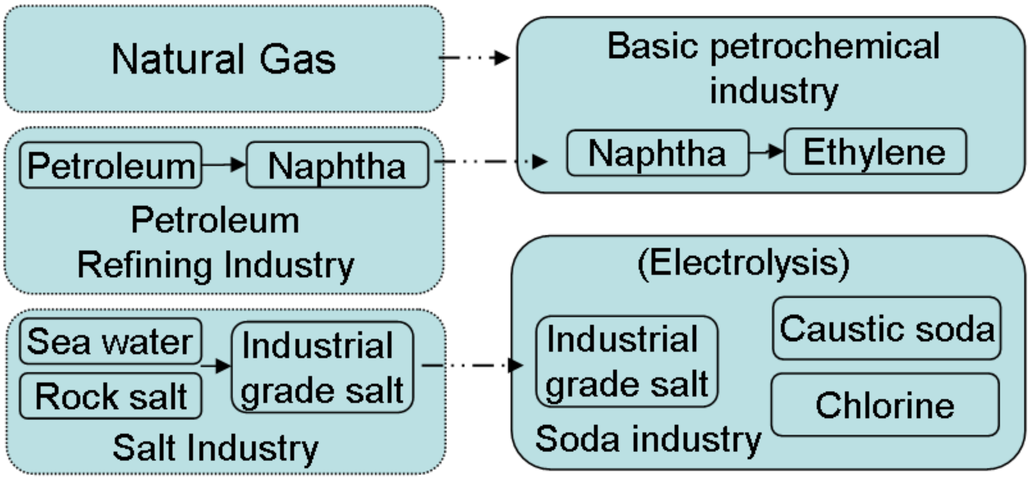

Figure 5.4 Industry pathway for the production of EDC inputs (modified from PVC.org n.d.)

As the PVC pipe process found in GaBi is generic, the blue colouring in the pipe used for the HKT system is not specifically accounted for. A portion of the documentation provided with GaBi 4 on the polyvinylchloride pipe (PVC) production process can be found in Appendix E. Selected LCI data for the creation of 1 kg of PVC pipe using the GaBi supplied PVC pipe process is shown in Table 5.2.

Table 5.2 Selected LCI data for the creation of 1 kg of PVC pipe using the GaBi 4 supplied PVC pipe process (GaBi 4 2006)

RER: Polyvinylchloride pipe (PVC) PlasticsEurope - 1kg	Inputs	Outputs
Technical quantities		
Energy (net calorific value) [MJ]	61.2420	16.6060
Mass [kg]	83.2270	3.7930
Environmental quantities		
CML2001 - Dec. 07, Acidification Potential (AP) [kg SO2-Equiv.]	0.0000	0.0141
CML2001 - Dec. 07, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	0.0000	0.0012
CML2001 - Dec. 07, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	0.0000	3.2709
CML2001 - Dec. 07, Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	0.0000	0.0012

5.3b.2 Cement Mix Production Process

The LCI data for cement mix in GaBi has been provided by USLCI. It is for a common type of cement mix called Portland cement. The data is cradle to gate, considered of good quality, applies to regional North America (RNA) and is from 2006.

Portland cement is a dry powder that is a key ingredient in making concrete. USLCI data for cement mix production represents an averaging of four Portland cement mix production processes. Portland cement is created using the following four basic steps:

> (1) Quarry and crush: extracting raw material from the earth, crushing to 5-cm (2-inch) pieces, and conveying and stockpiling.
>
> (2) Raw meal preparation: recovering materials from stockpiles, proportioning to the correct chemical composition, and grinding and blending.
>
> (3) Pyroprocess: processing raw meal to remove water, calcining limestone and causing the mix components to react to form clinker, cooling and storing the clinker.
>
> (4) Finish grind: reclaiming the clinker from storage, adding gypsum and grinding to a fine powder, and conveying to storage. (NREL 2006, 1)

A portion of the documentation provided with GaBi 4 on the Portland cement production process can be found in Appendix E. Selected LCI data for the creation of 1 kg of Portland cement using the GaBi supplied Portland cement process is shown in Table 5.3.

Table 5.3 Selected LCI data for the creation of 1 kg of Portland cement using the GaBi supplied Portland cement process (GaBi 4 2006)

US: Portland cement, at plant USLCI/PE - 1kg	**Inputs**	**Outputs**
Technical quantities		
Energy (net calorific value) [MJ]	5.5093	0.0000
Mass [kg]	2.8574	2.3618
Environmental quantities		
CML2001 - Dec. 07, Acidification Potential (AP) [kg SO2-Equiv.]	0.0000	0.0069
CML2001 - Dec. 07, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	0.0000	0.0005
CML2001 - Dec. 07, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	0.0020	1.3737
CML2001 - Dec. 07, Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.]	0.0000	3.87E-09
CML2001 - Dec. 07, Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	0.0000	0.0004
CML2001 - Dec. 07, Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB-Equiv.]	0.0000	0.0039

5.3c Use phase

The main use phase processes for this section of the HKT hydropower system involves the transformation of land, the collection of water to be made available to the penstock and maintenance and repair of equipment and materials. While the life spans of individual materials vary within the model, the overall lifespan for the section has been set at 20 years. Replacements occurring within the 20 year span involve the periodic replacement of the stands used to support the canal and the bamboo cage used as a framework for debris filters.

5.3c.1 Land use and land use change

Resistance to the flow of water by the weir has created a small 5 metre(m) by 5m (rough measurement that includes weir footprint) reservoir behind the weir. Area now occupied by the reservoir was formerly riverbank and forest. The canal covers roughly 25m x .25m of forest and rests on both the ground and wooden stands. The settling tank covers a .5m^2 area that was formerly forest. An estimated 2m x 35m area of the river between the intake and settling tank also sees potential land use change from reduced river flow. The hydropower scheme reduces river flow in this section by over half during the driest times of the year and day and exposes part of the river bed. Appendix F provides an overview and calculations for land use footprints for HKT.

5.3c.2 River water use

HKT design calls for no more than half of the river's flow to be removed for power generation (BGET 2006b). The amount of water removed from the river by the intake and sent to the settling tank is greater than the amount of water that enters the penstock and is used for power generation. This extra water, which is allowed to overflow from the settling tank and follow a newly created dirt canal back to the river, is not included in the model. With the exception of periods when the system is not operating, the model uses all water collected by the intake for power generation.

5.4 Section 2: Penstock

The penstock transports water from the settling tank to the turbine. The HKT penstock covers a horizontal distance of 172m and moves water through a roughly 30m change in altitude (also called, head). The penstock consists of four inch PVC pipe connected using PVC solvent. The penstock is stabilized where necessary using concrete and local wood. Water is pressurized over the entire length of the penstock. Figure 5.5 shows the main components of this section.

Figure 5.5 Photos of penstock as installed in HKT

5.4a Process overview and construction materials

Figure 5.6 below shows a process overview for this section of the HKT hydroelectric system.

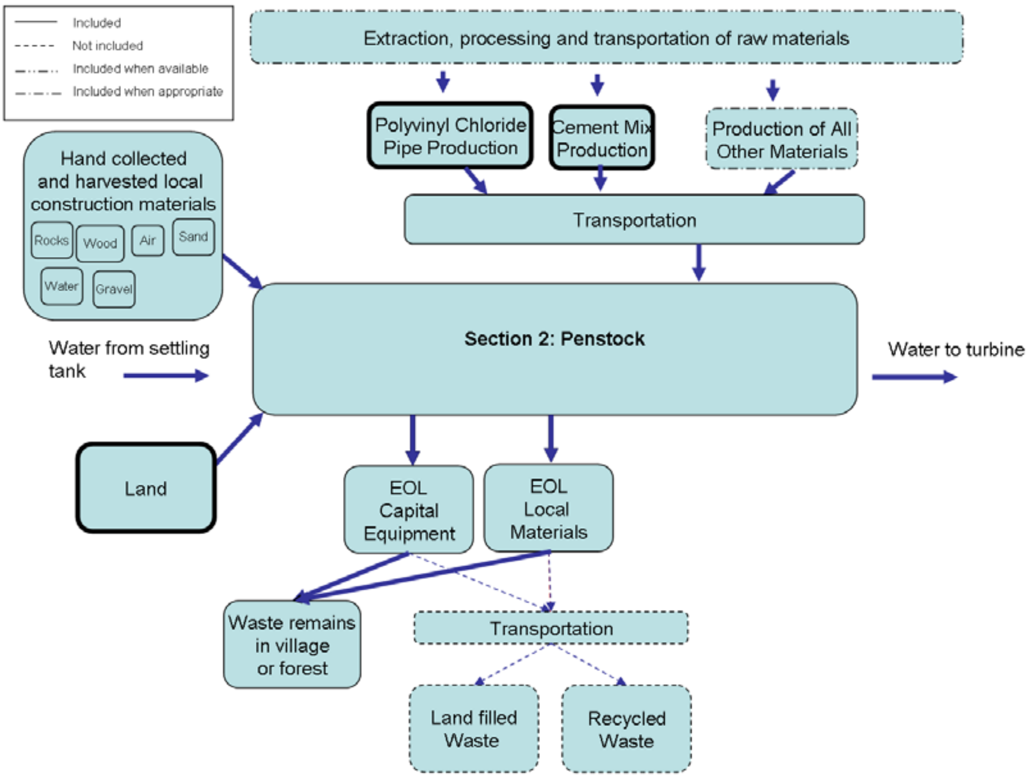

Figure 5.6 Process overview for HKT system penstock

Table 5.4 shows the life cycle material and land inputs used in modelling this section of the system. GaBi 4 process plans along with additional sub-plans for processes for this section can be found starting with Figure D-14 of Appendix D.

Table 5.4 20 year life cycle materials inputs for penstock

Item	Quantity	Unit	HKT Total Mass (kg)
Bags of dry cement mix for thrust blocks	3.00	bags	150.00
Schedule 40 - 4" inch blue PVC for penstock	172.00	m	514.49
Galvanized nails for fastening penstock supports	180.00	pce	2.10
PVC glue/solvent for penstock	4.00	can	4.00
Bailing wire to tie penstock to stands	240.00	m	1.47
Local wood support structure for penstock	60.00	pce	4756.58
Gravel Mixers added to dry cement to make wet concrete for penstock	289.52	kg	289.52
Sand Mixers added to dry cement to make wet concrete for penstock	152.38	kg	152.38
Water and Air Mixers added to dry cement to make wet concrete for penstock	23.84	kg	23.84
Forest to penstock	21.84	sqm	
Reduced flow in river between settling tank and outflow	400.00	sqm	

5.4b Production phase

Processes of interest in this section involve the production of polyvinyl chloride (PVC) pipe and the production of Portland cement. Both have already been detailed.

5.4c Use phase

The main use phase processes for this section of the HKT hydropower system involve the transformation of land and maintenance and repair of penstock equipment and materials. While the life spans of individual materials vary within the model, the overall lifespan for the penstock has been set at 20 years. Replacements occurring within the 20 year span involve the periodic replacement of stands used to support the penstock.

5.4c.1 Land use and land use change

The penstock covers roughly 172m x 0.127m (diameter of PVC pipe) of forest land between the settling tank and powerhouse. It rests on both the ground and wooden stands. A portion of the river between the settling tank and power house outflow also sees potential land use change through reduced water flow. The hydropower scheme reduces river flow between the settling tank and powerhouse outflow by up to 50% during the driest times of the year and day[10] and exposes parts of the river bed.

5.5 Section 3: Powerhouse, turbine and outflow (tailrace)

This portion of the hydroelectric system harnesses the power in flowing pressurized water to make electricity. Spent water is released via the outflow. The turbine, which takes in pressurized water and outputs electricity and spent water, makes this possible. Huai Kra Thing's turbine consists of a 4kW centrifugal pump which is being employed in reverse as a 3kW "pump as turbine" (PAT)[11] to electrify the community. A powerhouse building constructed of local materials protects the PAT and associated electrical gear. The outflow, also known as the tailrace, consists of a length of PVC pipe and a concrete ring. Figure 5.7 shows the main components of this section.

Figure 5.7 Photos of powerhouse, turbine and outflow from HKT

5.5a Process overview and construction materials

Figure 5.8 below shows a process overview for this section of the HKT hydroelectric system.

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[10] Daily tidal variation can be observed on site.

[11] Instead of using electricity to pump water up a slope, a PAT uses a pump running backwards to take water running down a slope and make electricity. This is not possible with all pump types and requires suitable pump characteristics. Reference material on PATs can be found in book form (Williams 1995) or online (Greacen & Kerins n.d.).

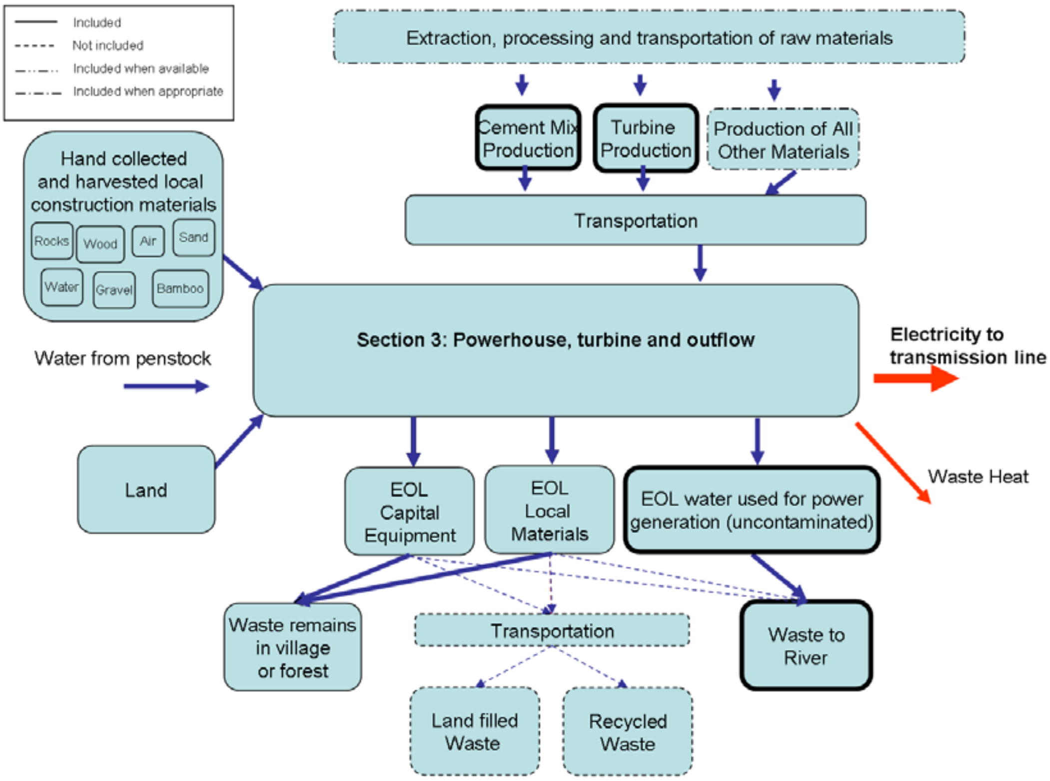

Figure 5.8 Process overview for HKT system powerhouse, turbine and outflow

Table 5.5 shows the life cycle material and land inputs used in modelling this section of the system. GaBi 4 process plans along with additional sub-plans for processes for this section can be found starting with Figure D-15 of Appendix D.

Table 5.5 20 year life cycle material inputs for powerhouse, turbine and outflow

Item	Quantity	Unit	HKT Total Mass (kg)
Galvanized steel sheets for powerhouse roofing	6.25	sqm	36.91
Galvanized nails for fastening powerhouse structure	628.00	pce	10.82
Bags of dry cement mix for concrete pad for turbine	4.00	bags	200.00
Schedule 40 - 6" inch blue PVC pipe for outflow	3.00	m	24.69
Schedule 40 - 4" to 6" male PVC adapter for outflow	1.00	pce	1.00
Schedule 40 - 4" inch blue PVC pipe screw adapter for outflow	1.00	pce	0.50
Schedule 40 - 4" inch blue PVC pipe 45 degree connector for buildup	2.00	pce	0.88
Schedule 40 - blue PVC pipe 4" to 3" reducer for buildup	1.00	pce	0.84
Schedule 40 - 3" inch blue PVC pipe screw adapter for buildup	5.00	pce	2.00
Concrete rings for outflow (made off site-purchased whole)	1.00	pce	50.00
25uF Motor run capacitors (380V)	40.00	pce	10.00
50uF Motor run capacitors (380V)	40.00	pce	10.00
Plasting housing for motor run capacitors and overspeed circuit breaker	1.00	pce	1.00
Bailing wire to tie down penstock in powerhouse	200.00	m	1.23
3" bronze gate valve for turbine/penstock buildup	1.00	pce	2.85
3" cast iron connector for turbine/penstock buildup	1.00	pce	1.07
7/16 steel J bolts/nuts/washers for mounting turbine to foundation	4.00	set	0.80
Single throw two pole breaker (6A) in power house for overspeed	1.33	pce	0.26
Red LED system operating light in powerhouse	4.00	pce	0.0014
Local wood for powerhouse structure	188.11	m	1590.66
Gravel Mixers added to dry cement to make wet concrete for power house foundation	386.03	kg	386.03
Sand Mixers added to dry cement to make wet concrete for power house foundation	203.17	kg	203.17
Water and Air Mixers added to dry cement to make wet concrete for power house foundation	31.78	kg	31.78
Bamboo walls for powerhouse structure	70.54	kg	70.54
Bamboo form and rebar for concrete pad	4.00	kg	4.00
4kW Ebara end suction volute pump with four pole 380V motor	4	pce	480.00
Forest to outflow	1.11	sqm	
Forest to powerhouse building	4.00	sqm	

5.5b Production phase

Production processes of interest in this section are the process of creating Portland cement and the processes covering the production of the system's turbine. Cement has already been detailed.

5.5b.1 Pump Production

The centrifugal end suction FS4HA pump/motor unit used as the turbine in the HKT installation is produced by Ebara and has a nameplate manufacture location of Japan. Although closer inspection of the unit finds that the motor is produced by another company, the pump/motor will be considered a single unit for modelling purposes. This simplification is supported by a 1998 conference paper written by two employees of the Ebara LCA Systems Department which models the pump and motor combination as a single unit (Okazaki & Kaneko 1999).

In recent EPDs, Swedish pump makers characterized the manufacture of their pumps as the "casting and machining of products, the components of which consist of cast iron, and the production of electric motors for the products" (Flygt

2009, 5; Grindex 2009, 6). Inspection of the GaBi 4 databases yielded no pump production process. The pump production process adopted in the model is an aggregate of various metal casting and machining process for which LCI data is available in GaBi 4 databases.

An estimation of Ebara FS pump materials is made using Ebara FS pump mass and MS pump material specifications provided by Okazaki and Kaneko (1999). The assumption that Ebara FS pump materials are similar to MS materials is supported by BGET documentation which lists key pump parts as a bronze impeller, cast iron casing, and stainless steel shaft (BGET 2006b). A list of estimated FS pump materials by percentage and weight is shown in Table 5.6.

Table 5.6 Estimated materials by percentage mass for Ebara FS pump

Materials by % and mass for Ebara FS pump (1)		
Pump Material	**%**	**Mass**
Cast Iron	64.60%	*71.06*
Electromagnetic steel	14.40%	*15.84*
Cabon Steel	6.00%	*6.60*
Steel	5.60%	*6.16*
Stainless Steel	4.20%	*4.62*
Bronze	2.20%	*2.42*
Copper	2.00%	*2.20*
Aluminum	0.70%	*0.77*
Other	0.30%	*0.33*
Total Weight	**100.00%**	**110.00**
(1) from Okazaki & Kaneko (1999)		

A list of the GaBi 4 database processes used to model pump materials is shown in Table 5.7. Processes were chosen using the assumption process described in subsections 4.4 – 4.7. Selected GaBi 4 documentation for each process is provided in Appendix E.

Table 5.7 GaBi 4 database processes used to model Ebara FS pump

Pump Material	GaBi 4 process used	Origin	Data Quality (%)	Country of Application	Reference Year
Cast Iron	DE: Cast iron part (sand casting) PE <pl>	PE	good	DE	2005
Electromagnetic steel	DE: Steel cast part alloyed PE <pl>	PE	good	DE	2005
Cabon Steel	DE: Steel cast part alloyed PE <pl>	PE	good	DE	2005
Steel	DE: Steel cast part alloyed PE <pl>	PE	good	DE	2005
Stainless Steel	DE: Stainless steel cold roll PE	PE	good	DE	2004
Bronze	DE: Copper mix (99,999% from electrolysis) PE	PE	good	DE	2002
	DE: Tin plate BUWAL	BUWAL	good	DE	1996
Copper	DE: Copper mix (99,999% from electrolysis) PE	PE	good	DE	2002
Aluminum	DE: Aluminium die-cast part PE <b>	PE	good	DE	2005

An initial comparison of the GaBi model with the energy consumption and CO_2 emissions results reported for the FS model pump in the LCA performed by Okazaki and Kaneko (1999) showed that 90% of energy flows and 82% of GWP were accounted for. When thermal energy was added to the process to partially account for missing energy in pump production and to bring energy accounting up to 100% of the value reported by Okazaki and Kaneko (1999), GWP impact rose to 90% of the reported value.

At this point, the model of the pump is assumed to be within the scope of this study. Missing energy and material flows are expected to be below cut-off values.

The model of the pump differs from all other HKT scheme components in that, where possible, it uses Japanese specific energy inputs in the creation of pump parts in order to more closely model the product. Japanese energy processes are sourced from GaBi 4 databases and apply to 2002. Selected LCI data from the modelling of 1kg of an Ebara FS pump is shown below in Table 5.8.

Table 5.8 Selected LCI data from the modelling of 1kg of an Ebara FS pump

Pump as Turbine - 1kg	Inputs	Outputs
Technical quantities		
Energy (net calorific value) [MJ]	27.22	11.09
Mass [kg]	34.10	19.49
Environmental quantities		
CML2001 - Dec. 07, Acidification Potential (AP) [kg SO2-Equiv.]	0.0000	0.0048
CML2001 - Dec. 07, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	0.0000	0.0008
CML2001 - Dec. 07, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	0.0000	2.4285
CML2001 - Dec. 07, Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.]	0.0000	1.77E-07
CML2001 - Dec. 07, Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	0.0000	0.0005

5.5c Use phase

The main use phase processes for this scheme component involve the generation of electrical power, waste heat sent to water, the outflow of water used in the generation of electricity, the replacement of components as they fail and the generation of noise. A small 5.1m^2 land use footprint is occupied by the powerhouse building and outflow.

5.5c.1 Generation of power from turbine

The turbine converts the power in flowing pressurized water to electrical power. A conversion rate of 1.6kW of electrical output power per ten litres a second of input water flowing through the turbine is detailed in the HKT installation report (Greacen 2006). As shown in Table 5.9 below, this represents a 48% efficient conversion of theoretical power to electrical power. Full calculations for this conversion can be found in Appendix J.

Table 5.9 Conversion of theoretical to electrical power

Consideration	Result	Unit
Theoretical power available at 10 L/s for HKT (no losses)	3334	W
Power Available from Turbine at 10 L/s after install	1600	W
Efficiency of Penstock, Turbine and Motor	**48%**	

5.5c.2 Waste heat to water and return of water to river

River water is released from the turbine via the outflow in this section of the HKT hydropower scheme. While river water is used for power generation, spent water is uncontaminated beyond waste heat generated by the turbine and friction between flowing water and system components. Waste heat transmitted to water is tracked in the model and considered significant. Maximum possible waste heat to water is calculated in Table 5.10 and uses results shown in Table 5.9.

Table 5.10 Calculation of maximum waste heat sent to water

a. Theoretical system power (see Table 5.5c.1.1)	3.334	kW
b. Actual power available from turbine (Table 5.5c.1.1)	1.6	kW
d. Hours a day	24	hours
e. Days a year	365.25	days
f. % year system operational	85%	
g. Years of system study	20	years
h. Maximum potential waste heat sent to water		
= (a - b) *d * e * f * g	**258,404**	**kWh**

Spent water rejoins the stream roughly 7m after it exits the outflow pipe. At 10 litres a second and an 85% annual operation figure, 5,364,792 m^3 of water will have been used over 20 years of power generation. Table 5.11 details the calculation of total lifetime water use for power generation. As discussed in Chapter 4, water used for power generation is not consumed in the LCA model.

Table 5.11 Calculation of water use for the HKT turbine

a. Water flow	10	l/s
b. Seconds in an hour	3600	seconds
c. Hours a day	24	hours
d. Days a year	365.25	days
e. % year system operational	85%	
g. Years of system study	20	years
f. Annual water used by turbine = a * c * d * e =	**268,240**	**m^3**
h. Lifetime water use calcualtion = f * g =	**5,364,792**	**m^3**

5.5c.3 Replacement of failed components

While the life spans of individual powerhouse, turbine and outflow materials vary within the model, the overall lifespan for the section has been set at five years. Turbine replacement is expected to occur every five years as is the replacement of the wood forming the powerhouse's structure. The bamboo walls covering the structure are replaced every two years. Motor run capacitors which are crucial in exciting the PAT to produce electricity are replaced every six months. Capacitor lifespan is based on anecdotal reports from BGET technicians.

5.5c.4 Noise generated by turbine

Noise at the powerhouse is mechanical in nature and roughly the same intensity as city traffic. The powerhouse is over a half a kilometre from the village.

5.6 Section 4: Transmission

This section of the hydroelectric system's function is to transmit electricity safely back to the control house where it is regulated and conditioned for distribution to the community. Electricity is transmitted along 600 metres (one-way) of 25mm^2 aluminium wire. The transmission wire is raised off of the ground by three metre tall, locally sourced wooden poles and connected to those poles using aluminium framed ceramic insulators. Wooden power poles are placed in hand dug holes and then concrete is added to the hole to provide further stability. Figure 5.9 shows pictures of components from this section.

Figure 5.9 Photos of transmission from HKT

5.6a Process overview and construction materials

Figure 5.10 below shows a process overview for this section of the HKT hydroelectric system.

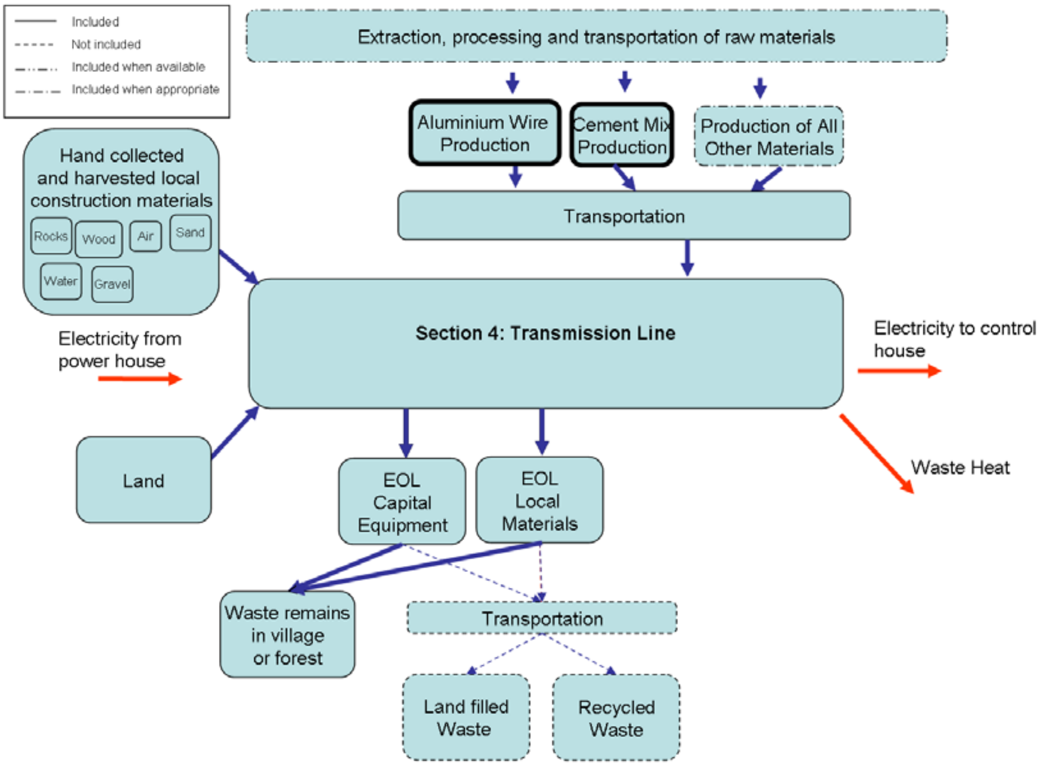

Figure 5.10 Process overview for HKT system transmission line

Table 5.12 shows the life cycle material and land inputs used in modelling this section of the system. GaBi 4 process plans along with additional sub-plans for processes for this section can be found starting with Figure D-26 in Appendix D.

Table 5.12 20 year life cycle material inputs for transmission line

Item	Quantity	Unit	HKT Total Mass (kg)
Bags of dry cement mix for transmission power pole bases	16.00	bags	800.00
Aluminum Wire 25sqmm for transmission - sheathed	1,200.00	m	136.20
Ceramic insulators in aluminium bracket for transmission line	40.00	pce	62.00
Aluminum wire to provide stress relief for transmission wires at pole - no sheath	80.00	m	0.68
Galvanized nails for fastening insulator structure to transmission pole	320.00	pce	3.73
Local wood for power transmission poles	160.00	pce	9513.15
Gravel Mixers added to dry cement to make wet concrete for transmission line	1544.13	kg	1544.13
Sand Mixers added to dry cement to make wet concrete for transmission line	812.70	kg	812.70
Water and Air Mixers added to dry cement to make wet concrete for transmission line	127.12	kg	127.12
Forest to transmission	15.39	sqm	

5.6b Production phase

Production processes of interest in this section are those for creating Portland cement and for creating aluminium wire. Ceramic insulators were modelled using a glass process and found to have less overall impact than cement or sheathed wire. They are not detailed in this section. Cement has already been detailed.

5.6b.1 Insulated aluminium wire production

Production of aluminium wire used to conduct electricity involves two central processes, the production of electrical grade aluminium wire and the coating of that wire with polymer insulation.

Electrical grade aluminium wire is produced using a process that starts with the mining and extraction of bauxite ore and ends with the drawing of an aluminium ingot into wire. Processes that occur in between include:

- refining of bauxite into alumina,
- creation of aluminium oxide and carbon dioxide from a process involving alumina, electricity and cryolite,
- collection of molten aluminium into ingots (The Aluminum Association 2008a),
- casting of molten aluminium into ingot, bar or rod (The Aluminum Association 2008b) and
- processing that turns ingot, rod or bar into wire.

One such ingot to wire process is described by The Aluminium Association.

> A long, square ingot is heated, progressively reduced in cross-section by passing it through a series of rolls, and then coiled. The coils are heated for softening and, if they are slated to become wire, the rod is pulled through smaller and smaller dies on a wire-drawing machine. Electrical conductor is made by stranding several wires into a single length. (The Aluminum Association 2008c)

Aluminium wire is then drawn through a die, like the one pictured in Figure 5.11, to apply insulation. A more detailed description is as follows:

> In wire and cable coating processes, individual wires or wire assemblies are pulled at very high speed through a crosshead die, at right angles to the extruder axis. In high pressure extrusion, the polymer melt meets the wire or cable before the die exit, e.g. for insulating of individual wires. (Vlachopoulos & Strutt 2003, 1167)

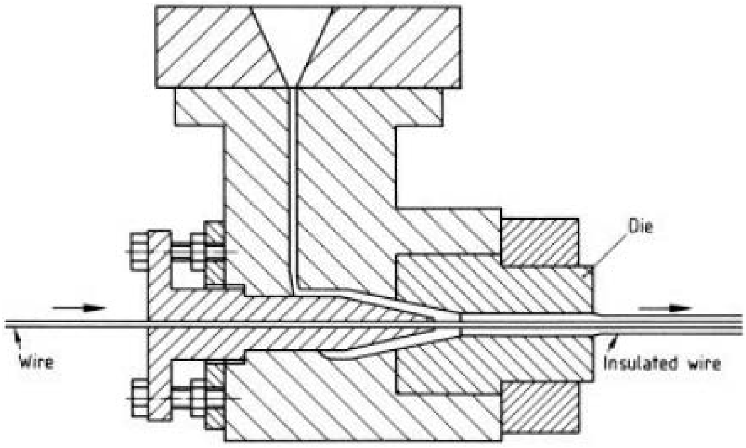

Fig. 7: Wire Coating Die

Figure 5.11 Die used for the insulation of Aluminium wire (Vlachopoulos & Strutt 2003, 1167)

Manufacturer specifications for the 25mm^2 aluminium wire used in the HKT scheme can be found in Appendix G. Specifications detail a stranded aluminium wire with black PVC insulation. Calculations performed on one metre of transmission wire found that the wire was 64% aluminium and 36% PVC by mass. These calculations can be found in Appendix H.

Using the assumptions and methods outlined in subsections 4.4-4.7, an aluminium ingot process was chosen as a substitute for aluminium wire creation and a polyvinyl chloride pipe process was chosen as a substitute for the sheathing process. Missing energy flows from the wire drawing process are estimated from quick calculations involving a GaBi 4 comparison between the net energy required to make 1kg of steel wire and 1kg steel billet, to be less than 4.14MJ per kg of finished product[12]. Although aluminium is a softer metal and the energy required to draw it is expected to be less than for steel wire, the same amount of energy needed for drawing 1kg of steel has been entered into the aluminium wire model to account for both wire drawing and standing. Missing material inputs that are expected to be below cut-off values are the plasticizer and black die used in the PVC sheathing.

[12] Aluminum is more ductile than steel.

Selected LCI data from the modelling of 1 kg of 25mm^2 PVC insulated aluminium wire is shown below in Table 5.13.

Table 5.13 Selected LCI data from the modelling of 1kg of 25mm^2 PVC insulated aluminium wire

Aluminum Wire 25sqmm - 1kg	Inputs	Outputs
Technical quantities		
Energy (net calorific value) [MJ]	118.51	9.20
Mass [kg]	48.05	13.63
Environmental quantities		
CML2001 - Dec. 07, Acidification Potential (AP) [kg SO2-Equiv.]	0.0000	0.0634
CML2001 - Dec. 07, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	0.0000	0.0024
CML2001 - Dec. 07, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]	0.0000	0.5080
CML2001 - Dec. 07, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	0.0000	9.3040
CML2001 - Dec. 07, Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.]	0.0052	2.38E-06
CML2001 - Dec. 07, Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	0.0000	0.0068

5.6c Use phase

There are no major use phase processes for this section of the HKT hydropower scheme. Three minor processes include land use change, waste heat production in the transmission line, and the replacement of components as they fail.

While land use might be expected to be a big input in this section, the HKT installation minimizes land clearing. Only the power pole bases are considered in the land use footprint. Appendix F shows calculations for this section's relatively minor land use footprint. Waste heat sent to air is negligible.[13] While the life spans of individual transmission line materials vary within the model, the overall lifespan for this section is set at 20 years. Wooden power pole replacement occurs every five years.[14]

5.7 Section 5: Control house, transformer, dump load and induction generator controller

[13] The production of waste heat in each step of the power generation process for HKT is unavoidable and a result of the physical properties of nature and inefficiencies in system electronics and machinery. The generation of waste heat from such sources has been included in the model but when sent to air is considered minor and will not be discussed here. An idea of how much waste heat is created can be estimated from system loss calculations occurring in Appendix H.

[14] It should be noted that these life spans assume that organic materials supporting penstock, canal and power transmission and distribution are well maintained and replaced without incident. If either regular maintenance or robustness of the scheme are in question, lifetimes of these components should be revisited.

This section controls turbine power output, prepares transmitted electricity for distribution to the village and sheds any excess energy. Central components of the control and conditioning equipment include a 3kW transformer which steps electricity down from 380V to 230V and a 3kW induction generator controller (IGC) which keeps a constant load on the turbine and diverts any excess power to a ballast load. The 3kW ballast load is also located in the control house. A small control house building protects the control equipment from damage and villagers and roaming animals from harm. Figure 5.12 shows pictures of components from this section.

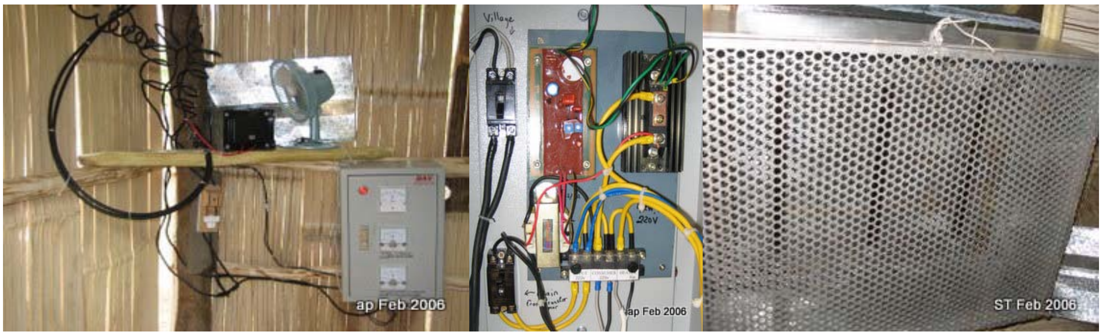

Figure 5.12 Photos of control house and power conditioning and control equipment from HKT. Transformer with fan and control box with metres (left), IGC, breakers and connection strip inside control box (centre), box containing dump load resistors (right)

5.7a Process overview and construction materials

Figure 5.13 below shows a process overview for this section of the HKT hydroelectric system.

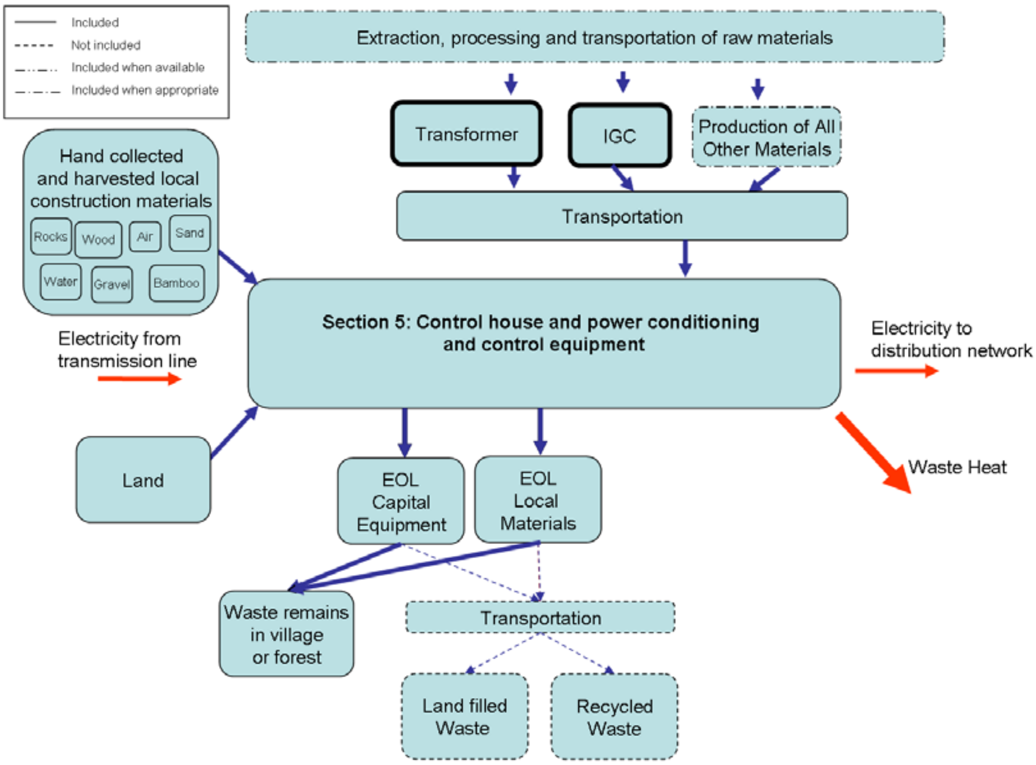

Figure 5.13 Process overview for HKT system control house and power conditioning and control equipment

Table 5.14 lists the life cycle material and land inputs used in modelling this section of the system. GaBi 4 process plans along with additional sub-plans for processes for this section be found starting with Figure D-30 in Appendix D.

Table 5.14 20 year life cycle material inputs for control house and power conditioning and control equipment

Item	Quantity	Unit	HKT Total Mass (kg)
Ceramic holders for resistive heating elements	6.00	pce	0.30
Galvanized steel sheets for control house roofing	6.25	sqm	36.91
Galvanized nails for fastening control house structure	608.00	pce	7.09
380 to 230Vac 50Hz Hand wound Power Transformer	4.00	pce	80.00
Steel ballast box (.25 x .8m locally made)	1.00	pce	8.00
Stainless steel electronics box - manufactured regionally	1.00	pce	5.00
23inch long 1kW resistive elements for ballast loads (FeCrAl)	6.00	pce	3.00
Single throw two pole breakers (15A and 20A) in control house	2.67	pce	0.53
Red LED system operating light in control house	4.00	pce	0.0014
Local wood for control house structure	183.15	m	1548.78
Bamboo walls for control house structure	68.68	kg	68.68
3kW Electric Load Controller (IGC) from Nepal	4	pce	3.8075
Forest to control house building	4	sqm	

5.7b Production phase

Production processes of interest in this section are those for the creation of the transformer and for the creation of the IGC.

5.7b.1 380/235 Vac 3kVA hand wound single phase transformer

Producing a hand wound power distribution transformer consists of the following basic steps on which there are many variations:

- producing copper wire;
- processing ferrosilicon to make silicon steel;
- producing thin sheets of grain oriented, cold rolled, silicon steel laminations;
- stacking cold rolled steel laminations alternately with thin insulating layers to form a core (Associated Transformers Pvt. Ltd 2008);
- turning insulated copper wire around the core to create a primary and secondary winding of the appropriate electrical relationship, and;
- protecting wound core.

A close up photo of the HKT transformer showing core laminations, protective end cap and access to the primary 380Vac winding is shown in Figure 5.14.

Figure 5.14 Close up photo of the HKT transformer showing core laminations, protective covering and access to primary winding

Initially, the hand wound transformer was modelled using 50% copper mix in place of copper wire and 50% cold rolled steel in place of a laminated steel core.[15] Such gross substitutions are missing the energy needed to make copper mix into copper wire, the 3% silicon and energy needed to make cold rolled silicon steel rather than cold rolled steel, the energy and insulating materials needed to make cold rolled steel into an laminated core and any insulating and protective materials required to make a finished transformer.

After a quick comparison with a coil transformer in the GaBi database indicated that up to 15% of input energy might be missing and as much as 11% of GWP impact, a scaled up version of the coil transformer in the GaBi database was chosen to represent the HKT transformer. Selected LCI data from the GaBi 4 process representing one kg of a hand wound transformer is presented in Table 5.15. Selected GaBi 4 documentation for the coil transformer can be found in Appendix E.

[15] Although an EPD exists for a three phase utility grade 63 MVA transformer (ABB Transformers 2004), it is a different enough from the hand wound 3kVA single phase inverter used at HKT that EPD inputs and outputs cannot simple be scaled down for use in modeling the HKT transformer.

Table 5.15 Selected LCI data for the production of one kg of the GaBi 4 database Coil Transformer process

DE: Coil transformer (DANFOSS A/S 175H0258) - scaled to 1kg	Inputs	Outputs
Technical quantities		
Energy (net calorific value) [MJ]	48.44	7.05
Mass [kg]	104.81	102.18
Environmental quantities		
CML2001 - Dec. 07, Acidification Potential (AP) [kg SO2-Equiv.]	0.0000	0.0167
CML2001 - Dec. 07, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	0.0000	0.0008
CML2001 - Dec. 07, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]	0.0000	0.0257
CML2001 - Dec. 07, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	0.0559	3.3540
CML2001 - Dec. 07, Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.]	0.0000	3.320E-08
CML2001 - Dec. 07, Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	0.0000	0.0015

5.7b.2 Induction Generator Controller

Hand production of an induction generator controller (IGC) consists of connecting the following main components to create a function unit: printed wiring board (PWB), through hole electrical components, protective materials and supporting electrical components such as a transformer and heat sink. Connections are hand made using wiring where necessary, solder and a soldering iron. A protective coating is applied to protect sensitive components on the printed wiring board. A description of the production of each of the components that comprise the IGC is beyond the scope of this LCA.

A picture of the IGC used at HKT is shown in Figure 5.15. A full description of how an IGC might be produced in conditions similar to those in Nepal is found in an unpublished but comprehensive and freely available manual by Jan Portegijs (2000) entitled, “The `humming bird' Electronic Load Controller / Induction Generator Controller”. Human labour rather than automated assembly line machinery is used in the production of an IGC.

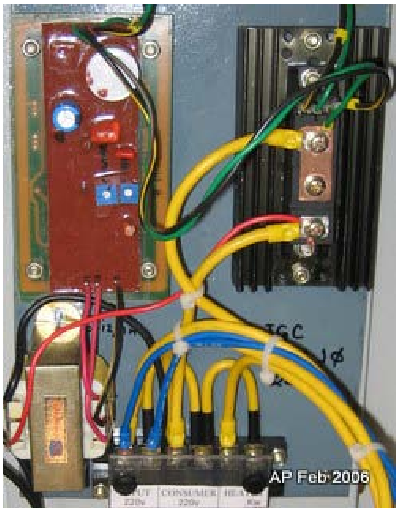

Figure 5.15 Picture of the induction generator controller (PWB, transformer, heat sink) used at HKT

Modelling of the IGC was achieved using the component list provided by Portegijs (2000) which can found in Appendix G. A list of the GaBi 4 database processes used to model the IGC is shown in Table 5.16. Processes were chosen using the assumptions and methods described in subsections 4.4-4.7. Selected GaBi 4 documentation for the printed wired board can be found in Appendix E.

Table 5.16 GaBi 4 database processes used to model IGC

GaBi 4 process used	Origin	Data Quality	Country of Application	Reference Year
DE: Resistor SMD (average) PE	PE	good	DE	2002
DE: Capacitor AL-ELKO General purpose (Average) PE	PE	good	DE	2002
DE: Diode SMD large (average) PE	PE	good	DE	2002
DE: Transistor SMD power large (average) PE	PE	good	DE	2002
DE: LED (average) PE	PE	good	DE	2002
RER: IC DIP/DIL (average) PE	PE	good	RER	2002
RER: Printed wired board FR4 (4l; 2s; AuNi finishing) PE	PE	good	RER	2002
DE: Copper mix (99,999% from electrolysis) PE	PE	good	DE	2002
US: Precision sand casting, aluminum USLCI/PE	USLCI/PE	good	US	2009
US: Iron, sand casted USLCI/PE	USLCI/PE	good	US	2009
Coil transformer Danfoss A/S (171,21 g)	PE	good	DE	2002

Component processes used in the model are mostly substitutes for listed parts as exact matches were unavailable. Certainty of substitution quality is low and many materials without a reasonably close match in available GaBi 4 databases have not been included. Selected LCI data from the GaBi 4 process representing 1kg of IGC is presented in Table 5.17.

Table 5.17 Selected LCI data for the production of 1kg of IGC using the created model

Induction Generator Controller - scaled to 1kg	Inputs	Outputs
Technical quantities		
Energy (net calorific value) [MJ]	332.36	161.71
Mass [kg]	592.41	454.81
Environmental quantities		
CML2001 - Dec. 07, Acidification Potential (AP) [kg SO2-Equiv.]	0.0000	0.1193
CML2001 - Dec. 07, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	0.0000	0.0056
CML2001 - Dec. 07, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]	0.0000	3.1820
CML2001 - Dec. 07, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	0.0000	21.2660
CML2001 - Dec. 07, Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.]	0.0000	2.571E-06
CML2001 - Dec. 07, Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	0.0000	0.0089

5.7c Use phase

Equipment replacement and waste heat generation by the dump load are the central processes of interest in this section. Land use change is minor and limited to the $4m^2$ footprint of the control house.

5.7c.1 Waste heat production in ballast

Waste heat is created when villagers do not use the full amount of power available to them in community buildings. All unused power turns into waste heat in the dump load's resistive heating elements. As detailed in Chapter 4, waste heat sent to air is considered negligible. Waste heat created in the dump load is not tracked in the model.

5.7c.2 Replacement of failed components

While the life spans of individual materials vary within the model, the overall lifespan for this section has been set at five years. IGC and transformer replacement occurs every five years which is in agreement with the electronic component life span estimates used in other rural electrification literature (Kenfack et al. 2009). The wood forming the control house's structure is replaced every five years and the bamboo walls of the structure every two.

5.8 Section 6: Distribution

This section of the HKT hydroelectric power scheme uses 1178m of $16mm^2$ aluminium wire to distribute electricity from the control house to seven community buildings. Community oriented buildings covered in the scheme are a Baptist church, a Catholic church, the village headman's house[16], a medical clinic, a primary school, the school teacher's quarters, and an open air community meeting centre. Aside from wire size, the materials used for distribution match transmission materials. Figure 5.16 presents a map of the village distribution network.

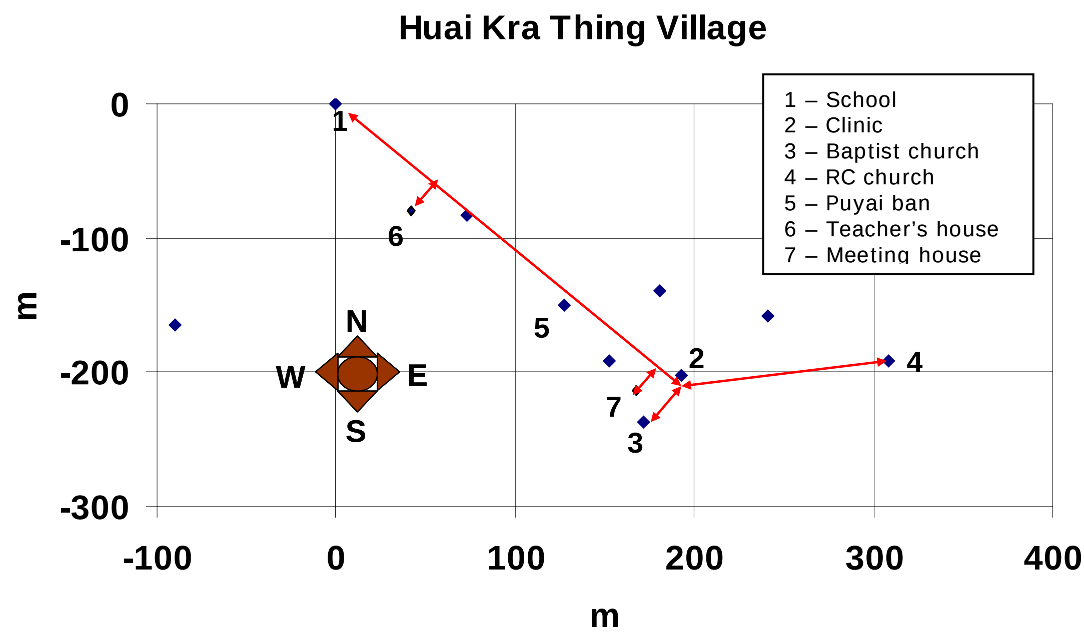

Figure 5.16 Power distribution map for HKT (modified from BGET 2006b)

5.8a Process overview and construction materials

Figure 5.17 below shows a process overview for this section of the HKT hydroelectric system.

[16] Puyai House in Figure 5.8.1. "Puyai" is roughly how the Thai word for village headman sounds in English.

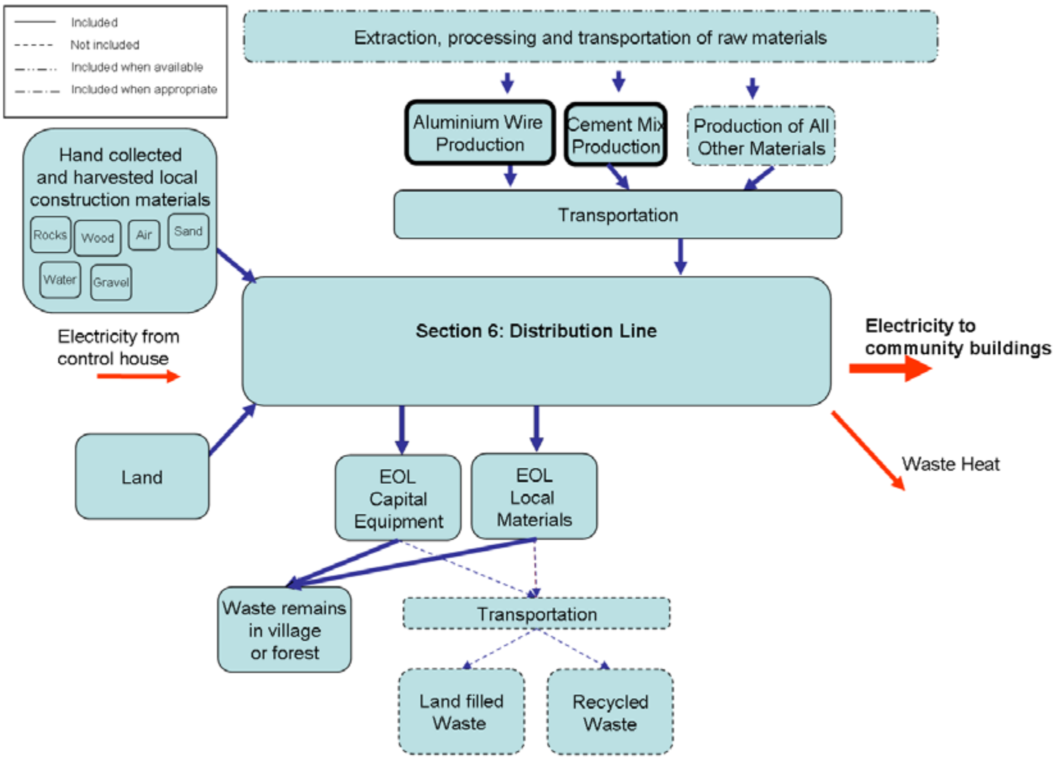

Figure 5.17 Process overview for HKT system distribution network

Table 5.18 lists the life cycle material and land inputs used in modelling this section of the system. GaBi 4 process plans along with additional sub-plans for processes for this section can be found starting with Figure D-36 in Appendix D.

Table 5.18 20 year life cycle material inputs for distribution network

Item	Quantity	Unit	HKT Total Mass (kg)
Bags of dry cement mix for distribution power pole bases	16.00	bags	800.00
Aluminum Wire 16sqmm for distribution - sheathed	1,178.00	m	86.82
Ceramic insulators in aluminium bracket for distribution line	47.00	pce	72.85
Aluminum wire to provide stress relief for distribution wires at pole - no sheath	94.00	m	0.80
Galvanized nails for fastening insulator structure to distribution pole	376.00	pce	4.39
Local wood for power distribution poles	160.00	pce	9513.15
Gravel Mixers added to dry cement to make wet concrete for distribution lines	1544.13	kg	1544.13
Sand Mixers added to dry cement to make wet concrete for distribution lines	812.70	kg	812.70
Water and Air Mixers added to dry cement to make wet concrete for distribution lines	127.12	kg	127.12
Forest to distribution	15.39	sqm	

5.8b Production phase

Production processes of interest in this section are those for creating dry cement mix and for creating aluminium wire. Both have already been detailed in previous sections.

5.8c Use phase

The use phase for this section involves the distribution of electrical power to the community buildings of HKT, the production of waste heat, the replacement of components as they fail and the land needed to distribute power to community buildings. The amounts of waste heat produced, land used for distribution and material required for the replacement of failed components are similar to those observed for the transmission line.

5.8c.1 Electrical power available at community buildings

The calculation summary presented in Table 5.19 finds that after losses, an average constant power of 1.47kW is available for use in community buildings. Background calculations are available in Appendix H.

Table 5.19 Summary of system efficiency and loss calculation results

Consideration	Result	Unit
Primary power to Electrical power		
Power Available from Turbine at 10 L/s after install	1600	W
Transmission Line Efficiency		
Calculated efficiency for Transmission Line	98%	
Power Available at Control House before Transformer	1576	W
Conversion and Control Efficiency		
Calcualted efficiency for Conversion and Control Equipment	94%	
Power available at CH after Conversion and Control Equipment	1482	W
Average Distribution Efficiency		
Average Efficiency for Distribution	99%	
Average Power available at connection to community structures	**1469**	**W**

5.9 Section 7: Building wiring and core energy services (lighting)

The final section of the HKT hydroelectric power scheme includes wiring and core energy services inside each building. Fused knife switches, fluorescent light bulbs, light fixtures, wall mounted switches and power points were installed in each community building connected to the system. No energy metering was included. Figure 5.18 shows pictures of components from this section. This section of the system is not included in the HKT model. The expectation that this section would be the same in all modelled power generation alternatives led to it being excluded from this iteration of the study.

Figure 5.18 Photos and sketches of building wiring and lighting

5.10 Production processes for all other materials

Figure 5.19 shows the equipment and materials that are included in and excluded from the GaBi HKT model. Subsections 4.4 - 4.7 describe the assumptions and methods used in modelling the production of included products. Refer to Appendix D for GaBi 4 process plans for all included equipment and materials.

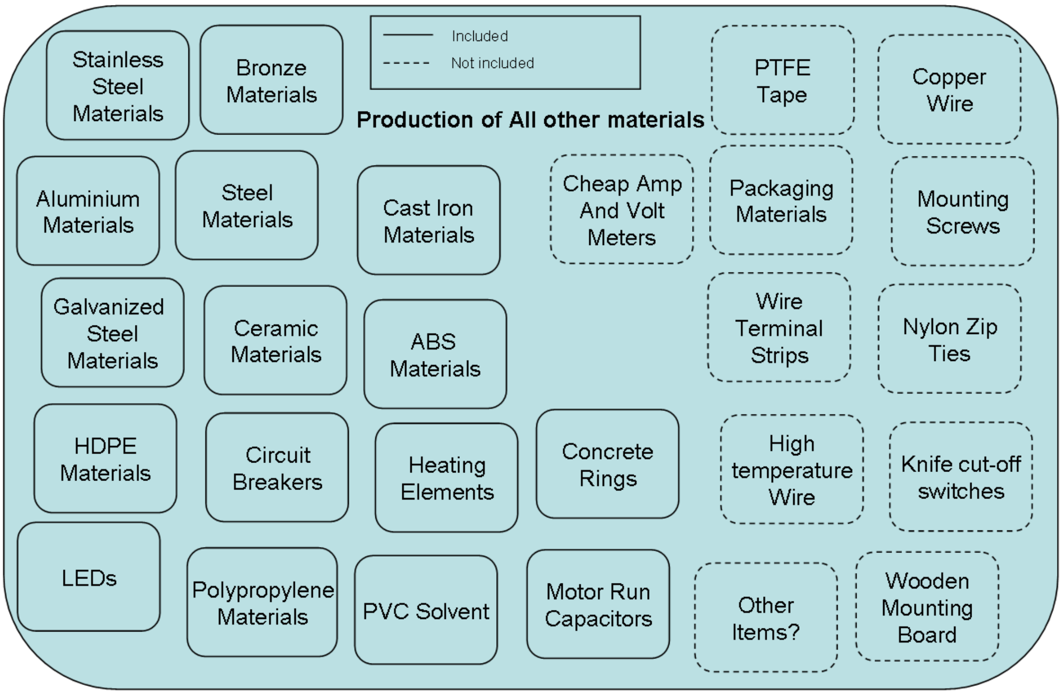

Figure 5.19 Production processes included and excluded from model

5.11 Transportation

Transportation is needed at three main points in the life cycle of the Huai Kra Thing electrification system. Transportation is needed within a country or region to transport materials required in the manufacture of equipment and to carry the finished product to a regional international shipping hub. Transportation is then needed to carry the product from that hub to Bangkok, the central distribution point for goods in Thailand. Once in Thailand, equipment requires transportation to arrive at its installed location as well as the location where it will end its life.

Table 5.20 presents all transport distances and modes used to model the flow of goods to and from the HKT hydropower scheme. Transportation related GaBi 4 process plans can be found in Appendix D starting with Figure D-41.

Table 5.20 Transport distances and modes used to model the flow of goods to and from the HKT hydropower scheme

Mode	From	To	Distance (km)	Source
Truck	Regional Japan	Tokyo	300	Estimate
Truck	RNA	Los Angeles	300	Estimate
Truck	RER	Rotterdam	300	Estimate
Truck	Regional Nepal	Kathmandu	300	Estimate
Ship	Tokyo	Bangkok	5,539	(Distances.com n.d.)
Ship	Rotterdam	Bangkok	17,346	(Distances.com n.d.)
Plane	Kathmandu	Bangkok	2,192	(WebFlyer n.d.)
Ship	Los Angeles	Bangkok	14,359	(Distances.com n.d.)
Truck	Bangkok, Thailand	Mae Sot	495	(Google & Tele Atlas 2010)
Truck	Mae Sot	Huai Kra Thing	65.2	(Google & Tele Atlas 2010)
Hand	Huai Kra Thing	Installation Site	0 - 1	(BGET 2006b)
Hand	Installation Site	End of Life	0 - 1	Estimate

5.11a Regional Transportation: Materials – Manufacturing – Shipping Hub

All equipment produced outside of Thailand is assumed to require an average of 250 highway km and 50 local road km of transport by diesel cargo truck to reach its regional hub. A sensitivity analysis in Chapter 9 will explore this further.

5.11b International Transportation: Shipping Hub - Bangkok

Once at a distribution hub, equipment is shipped to Bangkok using the distances and modes shown in Table 5.11.1. For example the turbine is transported from Tokyo to Bangkok on a cargo ship. The IGC is transported from Kathmandu to Bangkok by plane. PVC pipe and aluminium wire travel from Rotterdam to Bangkok on a cargo ship. Portland cement travels from Los Angeles to Bangkok on a cargo ship.

5.11c Thailand Transportation: Bangkok – HKT – End of Life

After arrival in Bangkok, equipment is transported to Mae Sot and then HKT using diesel cargo trucks. The model assumes non-villager workers providing labour for system installation accompanied equipment during transport from Mae Sot to HKT. However, additional diesel fuel needed to transport worker mass is not included in the model. Neither is worker transportation to HKT by motorbike. Both are expected to be below cut-off criteria.

After arriving in HKT, all materials are hand carried to their final destination. EOL transportation is assumed to be 100% human powered and no greater than 1km.

5.12 Scaling of impacts to functional unit

All LCIA results produced by the GaBi 4 model of the HKT hydropower system need to be scaled to the functional unit for this LCA. This is achieved by calculating total lifetime energy available to villagers at point of entry to community buildings and then dividing LCIA results by the total lifetime energy. Total lifetime energy available to villagers at point of entry to community buildings is calculated to be 218,977 kWh as shown in Table 5.21.

Table 5.21 Summary of system efficiency and loss calculation results

Total lifetime energy (kWh)	= average power available at community buildings (1.469 kW) * hours in a year (24 hours/day * 365.25 days/year) * % of year system is operational (85%) * length of study (20 years)	**= 218,977 kWh**

5.13 Diesel generator system model

The diesel generator system model created for this study uses a centralized 7kVA[17] diesel generator to make 1469 watts available to community buildings for 85% of the year. As with the HKT hydropower model, the study is not concerned with whether or not the power is consumed by villagers, but that the power is available. The generator is located in a building in the same location as

[17] The size of the diesel generator chosen for the model is based on the smallest generator the author could find in Mae Sot that was rated for 24 hour production.

the hydropower control house. The building itself is constructed in the same fashion as the powerhouse building but is two times the floor footprint to allow for fuel storage. The same distribution grid is used. All diesel fuel consumed is transported from Bangkok by way of Mae Sot. The end of life phase of the diesel generator system is the same as for all HKT hydroelectric system. All materials and equipment do not leave the HKT region.

5.13a Process overview and construction materials

Figure 5.20 below shows a process overview for the diesel generator system.

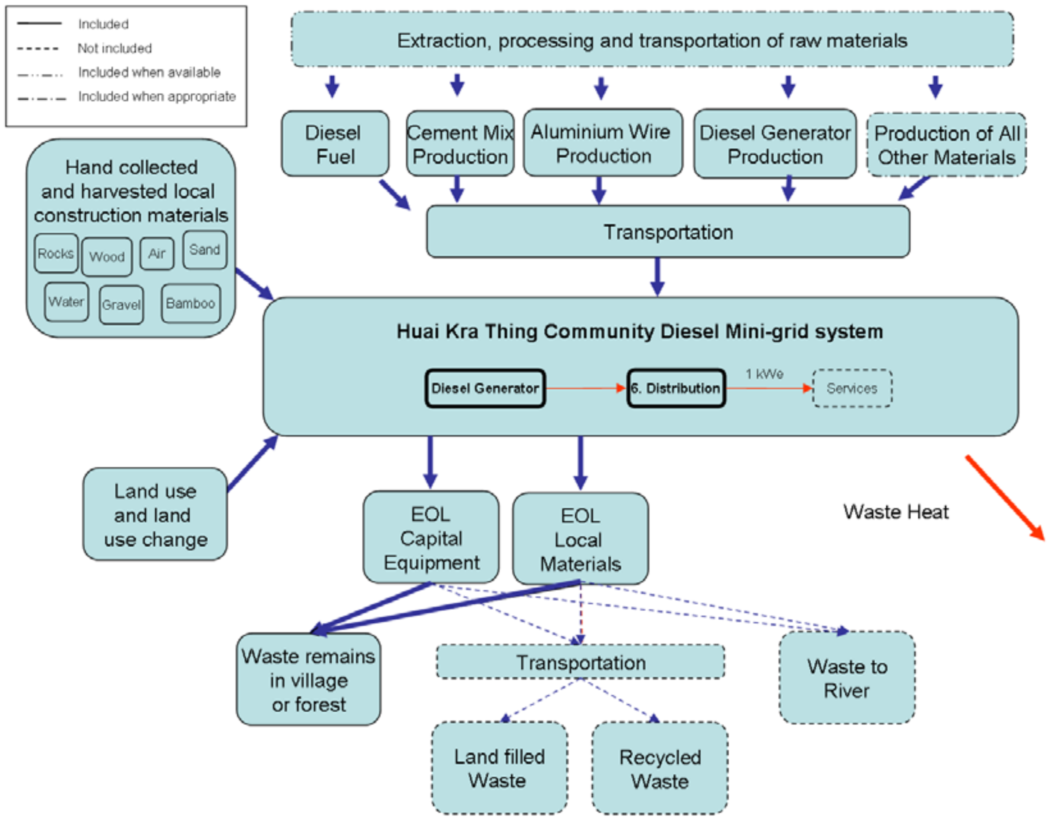

Figure 5.20 Process overview for diesel generator system model

Table 5.22 lists the life cycle material and land inputs used in modelling the diesel generator system. The list includes the specification of one distribution network and two powerhouse structures.

Table 5.22 20 year life cycle material inputs for diesel generator system

Item	Quantity	Unit	HKT Total Mass (kg)
Powerhouse structures	2	pce	5068
Distribution Networks	1	pce	12962
7kVA Diesel Generator	2	pce	550
Village to building	8	sqm	
Village to distribution network	15.4	sqm	
Diesel Fuel	88,338	l	73985

The distribution network is exactly the same as the one detailed in subsection 5.8. The powerhouse structure is exactly the same as the one used in the HKT hydropower system except that it is twice the size. GaBi process plans for the additional processes in this model can be found in Appendix M.

5.13b Production phase

Production processes of interest in this section are for diesel fuel and the diesel generator itself. A description of the production of diesel fuel and the diesel generator are considered beyond the scope of this study. Diesel fuel with a sulphur content of 500ppm is produced according to the selected GaBi 4 database process (GaBi 4 2006). The diesel generator was modelled according to the material specifications provided by Alsema (2000) which specify 30% cast steel, 30% steel, 35% aluminium, 3% plastic and 2% copper. The diesel generator's weight of 275kg was taken from industry literature (Hoa Binh Corporation n.d.) and anecdotal consultation with local vendors in Mae Sot. Production of system support materials such as the fuel storage tanks is ignored in the model as it is expected to be beneath all cut-off levels.

5.13c Use phase

The use phase of the diesel system involves land use change, transportation of diesel fuel to HKT, the operation of the generator and equipment maintenance.

5.13c.1 Land Use Change

Land occupied by the system is minor. The footprint consists of two powerhouse structures (2 x 4m^2 = 8m^2) plus the village distribution network (15.4m^2). Land use change resulting from occupation is also minor as land converted for the system is already cleared village land.

However, the determination of land use change occurring as the result of diesel fuel spilled or leaked into the materials of the powerhouse and area surrounding it are not as easy to gauge and represent an important local ecological impact factor.

5.13c.2 Transportation of diesel fuel to HKT

The substitute diesel fuel refining process used in to model the fuel production process is assumed also to account for transportation of diesel fuel from foreign ports to Bangkok. Transportation of fuel from Bangkok to HKT then occurs using the same Bangkok to HKT transportation processes used for all other materials and equipment. The model assumes that the differences between equipment and fuel transportation from Bangkok to HKT are small enough to ignore in the model and that no fuel is leaked or spilled over the entire 20 year operation of the system at HKT.

5.13c.3 Operating the generator to produce electricity

The diesel generator produces electricity from diesel fuel by combusting diesel fuel in a diesel engine. The diesel fuel used in this model has a sulphur content of 500ppm (GaBi 4 2006). In the process of generating 1kWh of electricity, 0.4 litres of diesel fuel are consumed and the selected pollutants listed in Table 5.23 are emitted (Alsema 2000). The assumption that the diesel generator produces 1kWh of electrical energy from 0.4 litres of diesel is a conservative estimate and may not represent actual consumption from the partially loaded generator chosen in this LCA (Fleck & Huot 2009; Hoa Binh Corporation n.d.).

Table 5.23 Selected emissions per kWh during generator operation (modified from Alsema 2000, A-9)

Emission	per kWh	Unit
CO_2	1.05168	kg
SO_2	0.2352	g
CO	0.3024	g
NOx	1.6128	g

The diesel generator system is modelled to make available 218,977 kWh of electrical energy at point of connection to HKT community buildings over 20 years. During this process 88,338 litres[18] of diesel fuel are consumed[19]. Table 5.24 presents the calculation for fuel consumed.

Table 5.24 Calculations for diesel fuel consumed by generator

Fuel consumed by generator (litres)	=	Total energy available at community building (see subsection 7.10) * litres diesel fuel per kWh electricity / Distribuiton Netowrk Efficiency (Appendix J)
	=	218,977 kWh * 0.4 litres per kWh / 0.9915
	=	**88,338**

5.13c.4 System maintenance, repair and equipment replacement

The diesel generator is assumed to have a life span of 10 years (Alsema 2000; Fleck & Huot 2009) and is replaced once over the 20 year study. Diesel generators also require regular maintenance and the repair and replacement of equipment. General maintenance involves the replacement of oil filters, air filters, fuel filters, lubricants and engine oil. Maintenance can be expected to occur every 600 hours of operation (Oparaku 2003) which would equate to servicing the HKT generator 12.4 times a year. As overall energy and mass flows for the servicing of the generator are expected to be below cut-off criteria, servicing is excluded from the current model. While the risk of impact on the HKT local environment from flows of oil and lubrication waste may not be negligible, they have been assumed to be negligible.

5.14 Grid Connection

Grid connection as modelled in this study assumes that the power grid has reached the nearest road system turn off point for the village and only 4km of

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[18] If the consumption figure of 0.53 litres/kWh from Fleck and Huot (2009) is used then 117,047 litres are consumed over 20 years.

[19] 76% of the energy content of diesel fuel, which is 10.72kWh/litre according to Fleck and Huot (2009), is wasted in this process. Most of this energy turns into waste heat. Waste heat created by the process and released to air is assumed to have a negligible environmental impact.

transmission line remains to be installed before power arrives in central HKT. The model created for this LCA consists of 4km of transmission line, a transformer, the distribution network in the village and the Thai power generation mix.

5.14a Process overview and construction materials

Figure 5.21 below shows a process overview for the connection of HKT to the Thai power grid.

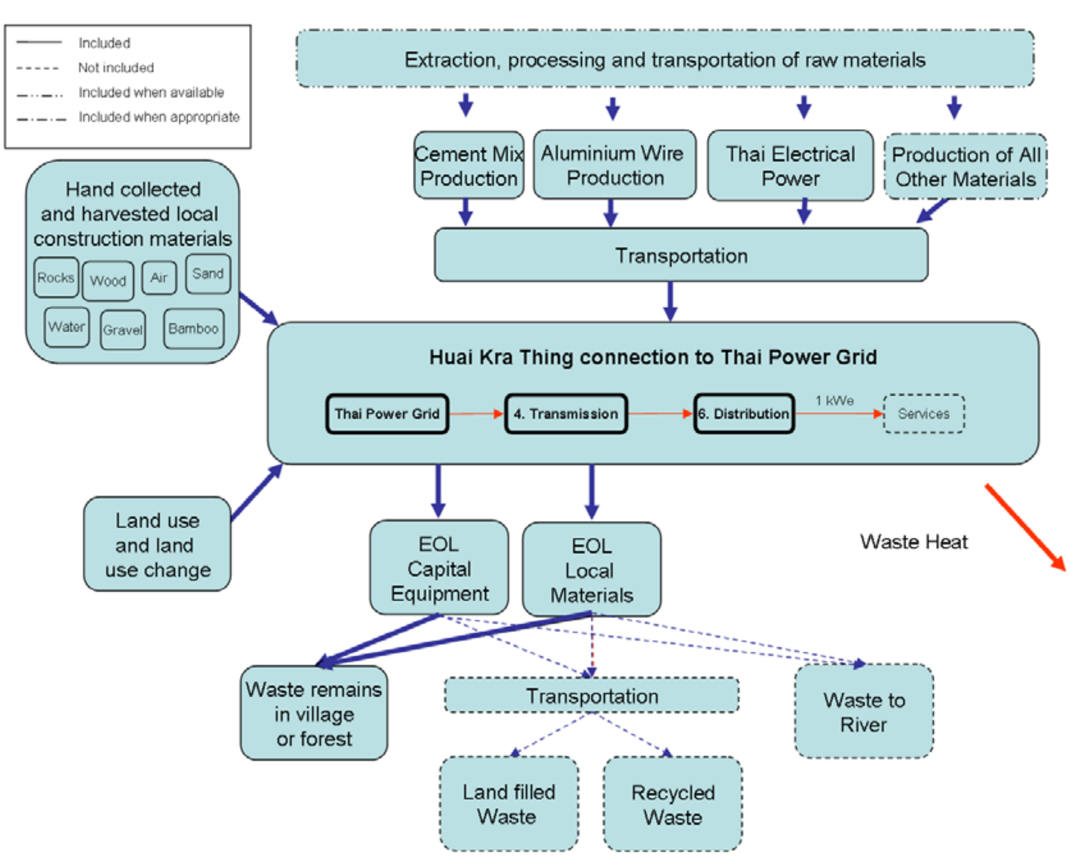

Figure 5.21 Process overview for Thai grid connection model

Table 5.25 lists the life cycle material and process inputs used in modelling a connection to the Thai grid system. The list includes the specification of one distribution network, six and two thirds transmission lines, four power transformers, and the GaBi 4 Thai power generation mix.

Table 5.25 20 year life cycle material inputs for Thai power grid connection

Item	Quantity	Unit	HKT Total Mass (kg)
Transmission Line	6.67	pce	13000
Distribution Networks	1	pce	12962
Transformer	4	pce	80
Forest to transmission line	103	sqm	
Village to distribution network	15.4	sqm	
GaBi Thai grid power	1	pce	

The distribution network is exactly the same as the one detailed in subsection 5.8. The transmission network is exactly the same as the one used in the HKT hydropower system except that it is 6.67 times as long.[20] The transformer used in this model is the same as used in the HKT hydropower model and is replaced four times over 20 years. Thai grid power is modelled using an "off the shelf" GaBi 4 process representing a cradle to gate process for Thai power generation mix. Selected documentation for this process can be found in Appendix E. The GaBi 4 process plans for the additional processes in this model can be found in Appendix N.

5.14b Production phase

Production processes of interest in this section deal with fuel processing and power station construction for the Thai grid power process. The Gabi 4 process used to model fuel processing and power station construction for Thai grid power applies to the year 2002 and is of good quality. Fuel carriers and power station types represented in the Thai grid power process are presented in Figure 5.22. A comparison of the 2002 process with the Thailand power generation mix for 2006 (OECD/IEA 2009) shows the 2002 process to be a reasonable substitute for the 2006 mix. Variations are minor and comprise a few percentage points. See Appendix E for further documentation on the Thai grid power processes.

[20] This model does not account for the fact that transmission and distribution poles used in the Thai national grid system are usually concrete.

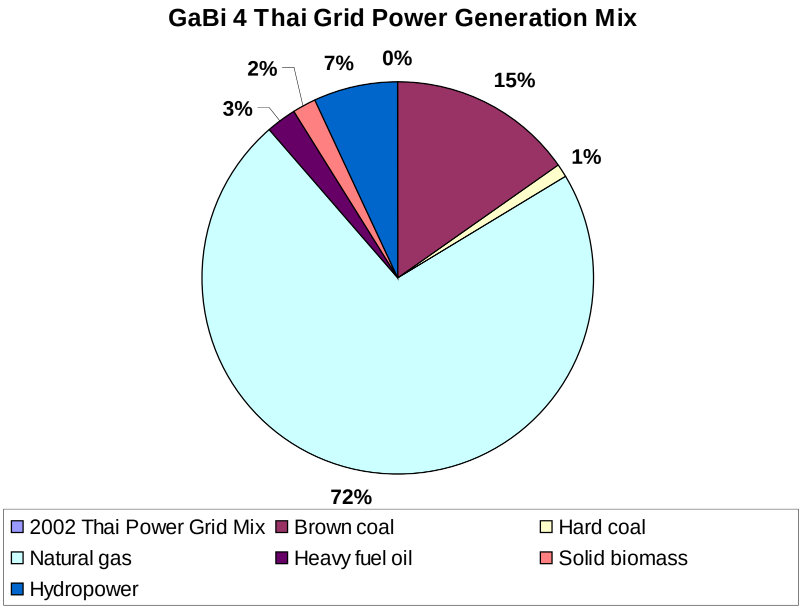

Figure 5.22 Percentages of the Thai grid power by energy carrier (modified from GaBi 4 2006)

The majority of the Thailand grid power is generated from natural gas (72%), brown coal (15%) and large hydropower (7%).

5.14c Use phase

The use phase of the grid connection system involves land use change and operation of the Thai grid power process.

5.14c.1 Land Use Change

Land occupied by the system consists of the village distribution network (15.4m^2) and land required for transmission. Applying the method previously used for land occupied by the transmission line returns 103m^2 (6.67 times 15.4m^2) of forest occupied by transmission line power pole bases. As this is an extension of the grid line and would have to meet national standards for the transmission of electricity, it is expected that even more land than calculated would be occupied by the lines. Land use change occurring as the result of the transmission grid extension along the road passing by the turn off to HKT is beyond the scope of this LCA.

5.14c.2 Generation of electricity by Thai grid power system

Electricity is produced from the mix of energy carriers detailed in subsection 5.14b. Each carrier has its own energy content, power generation process and emission profile (GaBi 4 2006). Selected LCI data from the GaBi 4 process representing the generation of one kWh of electricity from the Thai power grid is presented in Table 5.26.

Table 5.26 Selected LCI data representing the generation of 1kWh of electricity from the Thai power grid

Characterization and Impact Category or Indicator	Unit/kWh	Thai Power grid mix
CML2001- Dec. 07 ADP	g Sb - Equiv.	5.59
CML2001- Dec. 07 AP	g SO2 - Equiv.	9.84
CML2001- Dec. 07 EP	g Phosphate - Equiv.	0.347
CML2001- Dec. 07 GWP 100 years	g CO2 - Equiv.	859.5
CML2001- Dec. 07 ODP, steady state	g R11 - Equiv.	4.07E-08
CML2001- Dec. 07 POCP	g Ethene - Equiv	0.586
Primary Energy Demand	kWh	3.231

The power grid mix model includes the average Thai power grid loss of 7.3% (GaBi 4 2006). An additional average HKT distribution loss of 0.85% is also included in the overall system model.

5.14d End of Life phase

The power grid mix model includes end of life considerations for Thai power plant construction materials. End of life considerations for materials used in national transmission and distribution networks are not included in the model (GaBi 4 2006).

6. Life Cycle Impact Assessment (LCIA) Results

LCIA results are presented for the HKT hydroelectric system, the diesel generator system and the system involving connection to the Thai power grid. Categories and indicators selected for impact assessment and comparison are listed in subsection 4.8. LCIA results are neither normalized nor weighted.

6.1 HKT Hydroelectric System

Selected LCIA results for the HKT hydropower scheme model are presented in Table 6.1 and Figure 6.1. Table 6.1 provides results per kWh for the entire scheme along with the contribution of each component to the total figure. Figure 6.1 presents the relative contribution of each component to LCIA results.

Table 6.1 Selected LCIA results for the HKT hydropower scheme model

Category or Indicator	HKT 3kW Hydropower Scheme Total	1. Weir, intake, canal and forebay	2. Penstock	3. Powerhouse, turbine and outflow	4. Transmission Line	5. Control House and control and conditioning equipment	6. Distribution
ADP (g Sb -e)	**0.264**	0.024	0.071	0.042	0.059	0.017	0.051
AP (g SO_2 -e)	**0.372**	0.026	0.065	0.042	0.118	0.017	0.105
EP (g PO_4 -e)	**0.030**	0.002	0.006	0.005	0.008	0.002	0.007
GWP (g CO_2 -e)	**52.7**	3.7	9.8	9.0	14.7	2.7	12.9
ODP (g R11 -e)	**3.133E-06**	4.179E-09	6.995E-09	4.181E-07	1.589E-06	7.686E-08	1.039E-06
POCP (g ethene -e)	**0.030**	0.002	0.005	0.003	0.010	0.001	0.009
PED (kWh)	**0.150**	0.015	0.046	0.029	0.025	0.011	0.023

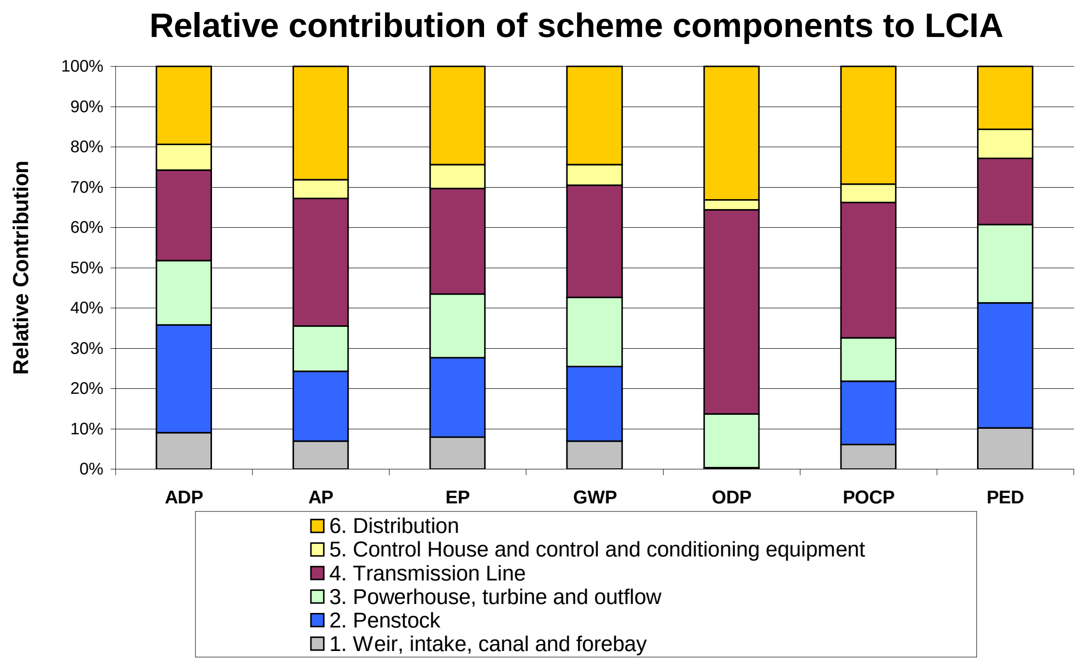

Figure 6.1 Selected LCIA results for the HKT hydropower scheme model

The transmission line (purple colour) is the dominant component in almost all LCIA impact categories with the exception of ADP and PED. The distribution network (orange) and penstock (blue) also represent a large percentage of selected LCIA results. Powerhouse equipment (green) contributes a larger share of PED, but is a small share in all other categories. Control house equipment (yellow) and the scheme civil works (grey) both comprise minor shares of all impact category results.

6.2 Diesel Generator

Selected LCIA results for the community grid connected diesel generator model are presented in Table 6.2 and Figure 6.2. Table 6.2 provides results per kWh for the entire scheme along with the contribution of each main component to the total figure. Figure 6.2 presents the relative contribution of each component to LCIA results.

Table 6.2 Selected LCIA results for a HKT community grid connected diesel generator[21]

Category or Indicator	HKT 7kVA Diesel Mini Grid for 0.4L/kWh	Distribution Network	Diesel Fuel Transportation	Diesel Generator 7kVA	Powerhouse building	Generator Operation	US: Diesel at refinery
ADP (g Sb -e)	**8.94**	0.05	0.23	0.10	0.02	0.00	8.54
AP (g SO_2 -e)	**2.82**	0.10	0.30	0.14	0.03	1.38	0.87
EP (g PO_4 -e)	**0.349**	0.007	0.054	0.008	0.003	0.211	0.065
GWP (g CO_2 -e)	**1361**	12.9	34.4	18.8	4.2	1114.6	176.0
ODP (g R11 -e)	**3.91E-06**	1.04E-06	6.83E-08	2.86E-07	2.07E-08	0.00E+00	2.49E-06
POCP (g ethene -e)	**0.231**	0.009	0.028	0.015	0.002	0.065	0.112
PED (kWh)	**5.20**	0.02	0.14	0.06	0.01	0.00	4.97

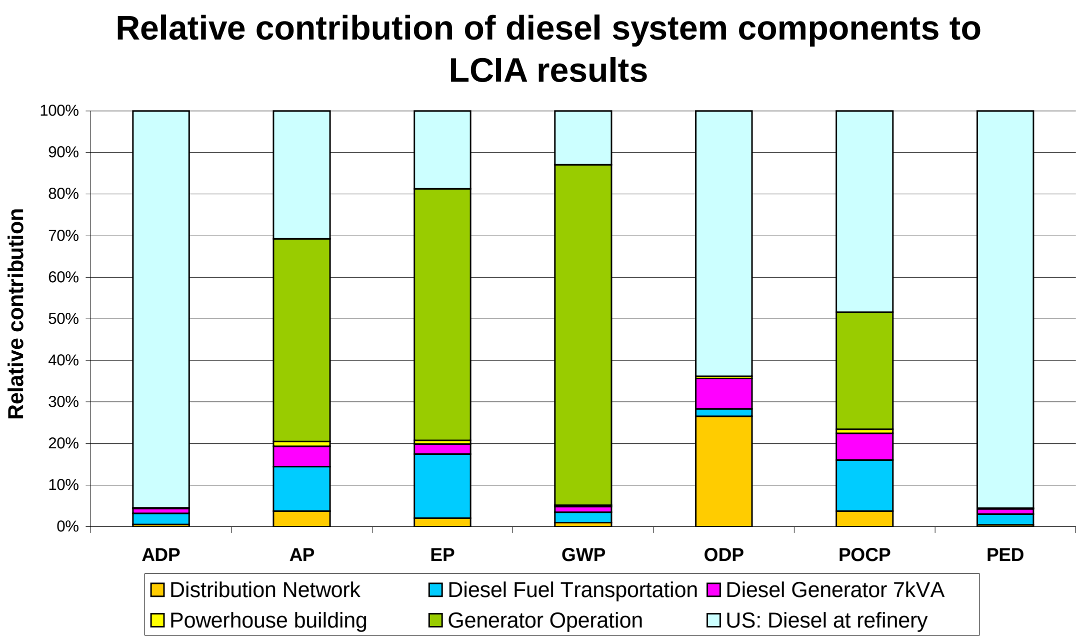

Figure 6.2 Selected LCIA results for a HKT community grid connected diesel generator

With the exception of the distribution network's (orange colour) contribution to ODP, the three items (yellow, orange, pink) representing the physical materials and equipment that comprise the diesel generator system all play relatively minor roles in the LCIA results. The distribution network's large ODP contribution stems from the production of aluminium wire needed for the network. The production of diesel fuel (light blue-green) contributes nearly all of the impact found in ADP, ODP and PED categories due to the large amounts of resources and energies involved. Diesel fuel production is also the single biggest

[21] If the 0.53 L/kWh consumption figure is used then results are ADP=11.80, AP=3.21, EP=0.39, GWP=1429, ODP=4.74E-06, POCP=0.28, PED=6.86

contributor to POCP due to high levels of non-methane volatile organic compound emission during the extraction of crude oil (Ally & Pryor 2007). Diesel generator operation (darker green) represents the majority of impact in AP, EP and GWP potential due to high operating emission levels of nitrogen oxide and carbon dioxide. After generator operation and diesel fuel production, transportation of the diesel fuel from Bangkok to HKT (blue) is the third biggest consistent contributor to all impact categories.

6.3 Connection to Thai Power Grid

Selected LCIA results for the model for connection to the Thai power grid are presented in Table 6.3 and Figure 6.3. Table 6.3 provides results per kWh for the entire scheme along with the contribution of each main component to the total figure. Figure 6.3 presents the relative contribution of each component to LCIA results. The Thai power generation mix label used in the following tables and figures represents the GaBi 4 model process for grid energy production in Thailand discussed in section 5.14 and Appendix E.

Table 6.3 Selected LCIA results for HKT connection to Thai power grid

Category or Indicator	**HKT Connection to Thai Power Grid**	Transmission Line	Distribution Network	Transformer	Thai power generation mix
ADP (g Sb -e)	**6.07**	0.37	0.05	0.01	5.64
AP (g SO_2 -e)	**10.78**	0.74	0.10	0.01	9.92
EP (g PO_4 -e)	**0.406**	0.049	0.007	0.001	0.350
GWP (g CO_2 -e)	**973**	91.9	12.9	1.4	866.8
ODP (g R11 -e)	**1.10E-05**	9.94E-06	1.04E-06	1.24E-08	4.11E-08
POCP (g ethene -e)	**0.663**	0.063	0.009	0.001	0.591
PED (kWh)	**3.60**	0.154	0.023	0.006	3.421

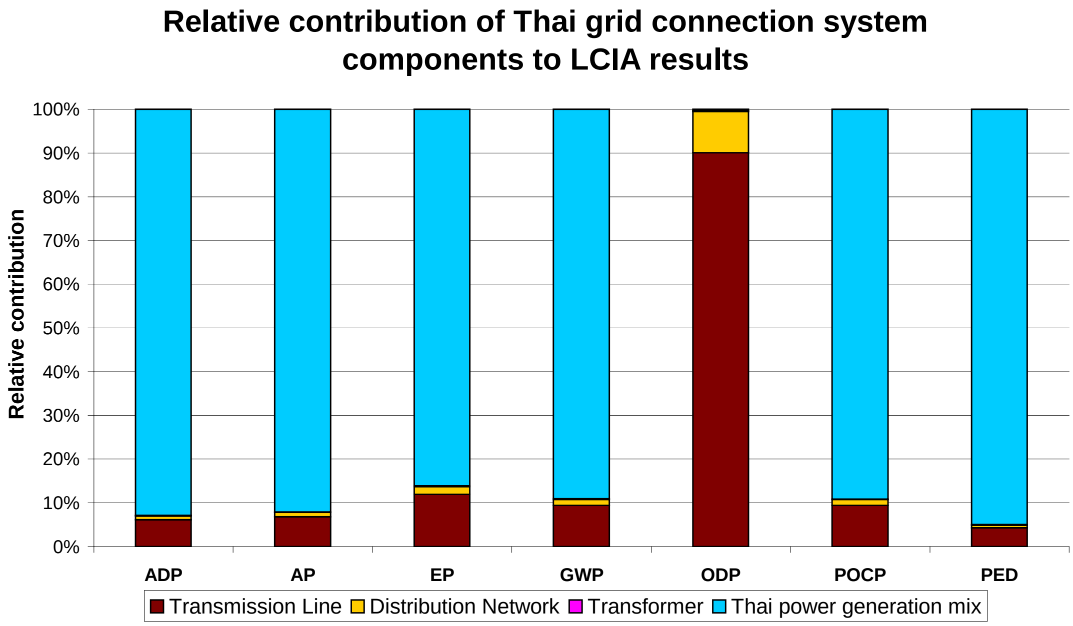

Figure 6.3 Selected LCIA results for HKT connection to Thai power grid

The production of fuels and generation of electricity from the Thai power grid (blue colour) dominates all impact categories with the exception of ODP. Over 98% of the ODP contribution in this system arises from the aluminium wire requirements of transmission (brown) and distribution (orange) networks. If the grid connection was to include local transmission and distribution networks up to the Thailand national standard, both the absolute LCIA values for the entire model and the relative contribution from these two components would increase.[22]

6.4 Comparison of schemes

Overall per kWh LCIA results for the three electrification options modelled in this LCA are compared in Table 6.4 and Figure 6.4 below.

[22] A preliminary sensitivity analysis shows that if wooded poles in the model were replaced by concrete poles closer in specification to Thai transmission and distribution poles, cement use would increase by 5%, thus increasing overall system environmental impact.

Table 6.4 Comparison of selected LCIA results for HKT hydropower and diesel generator min-grid schemes

Category or Indicator	HKT 3kW Hydropower Scheme Total	HKT 7kVA Diesel Mini Grid for 0.4L/kWh	HKT Connection to Thai Power Grid
ADP (g Sb -e)	0.264	8.94	6.07
AP (g SO_2 -e)	0.372	2.82	10.78
EP (g PO_4 -e)	0.030	0.349	0.406
GWP (g CO_2 -e)	52.7	1361	973
ODP (g R11 -e)	3.133E-06	3.91E-06	1.10E-05
POCP (g ethene -e)	0.030	0.231	0.663
PED (kWh)	0.150	5.20	3.60

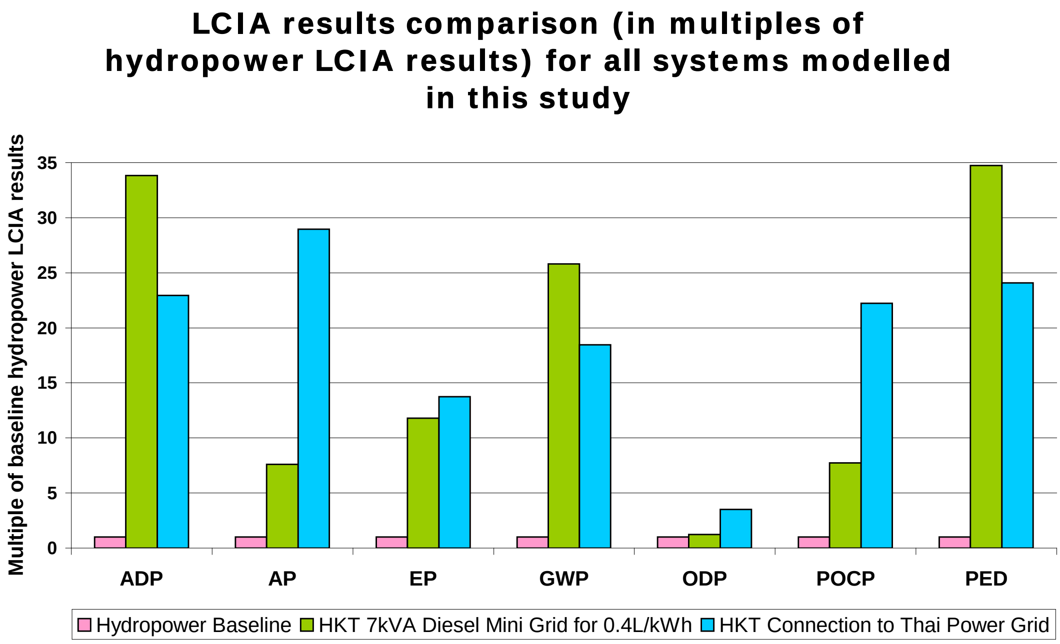

Figure 6.4 Comparison of selected LCIA results for HKT hydropower and diesel generator min-grid schemes. The HKT hydropower system is set to one and used as a baseline

With the exception of Ozone Depletion Potential, the HKT hydropower system's environmental credentials are clearly demonstrated. All LCIA results with the exception of ODP show seven to 34 times lower impacts than alternative systems. ODP grouping is due to the similarities and relative contribution of transmission and distribution networks in each system. For an equal amount of available power and energy, the HKT hydroelectric system has a significantly lower overall LCIA profile than either grid extension or a diesel system.

6.5 Land Use Change

Land use is an important part of local environmental considerations. Land use change is reported in this section purely as the area changed by the implementation of each electrification system. No attempt is made to quantify the environmental impacts of land use change associated with each type of change. Land use estimates are limited to the local HKT region. Land use change incurred during each system's end of life phase has not been included and is expected to be negligible.

6.5a HKT Hydroelectric System

Even though HKT design and construction philosophy follows a "soft approach", land occupied by the scheme has changed. Total land occupied by the HKT hydropower scheme is roughly calculated to be $93.59m^2$ in Appendix F. Figure 6.5 presents the relative contribution of each component to the total land use for the HKT hydropower system.

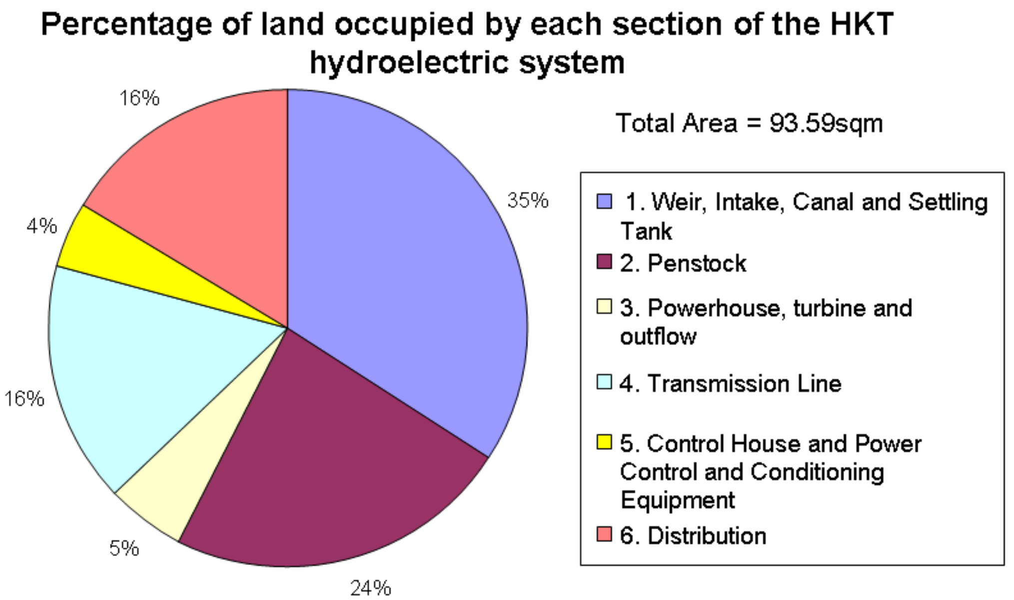

Figure 6.5 Percentage of land occupied by each section of the HKT hydroelectric system

Despite less than $100m^2$ of land being occupied by the scheme, $470m^2$ of additional land use change is potentially associated with the HKT hydropower scheme. Reduced flows in the river between intake and outflow as shown in Appendix F create the potential for change in the riverbed. Due to both seasonal and diurnal river fluctuations, land use change in the river is much harder to see and prove than land use change observed in the conversion of forest to building.

6.5b Diesel Generator

The system is estimated to occupy 23.4m^2 of village land. This land is part of the village footprint and is already clear of forest. Land use change occurring as the result of occupation by the system is negligible. However, the potential of diesel fuel leakage and spillage from fuel transport and system operation is not. Due to a lack of data, no estimate can be made of the potential and risk for land use change occurring from diesel fuel contamination.

6.5c Thai power grid connection

The system is estimated to occupy 15.4m^2 of village land and a minimum of 103m^2 of forest in the HKT region. More stringent national grid system requirements and an additional allocation of land from extension of the grid to the HKT region is expected to increase this figure significantly.

6.5d Comparison

A comparison of total land use change associated with the systems is presented in Table 6.5. The table also presents areas of potential change requiring further study.

Table 6.5 Comparison of land use change between HKT hydro and diesel systems – including areas of potential change requiring further study

Category	**HKT hydropower**	**Diesel system**	**Thai Grid Extension**
Total land occupied	93.6m^2	23.4m^2	118.4m^2
Additional potential land use change	470m^2	?m^2	?m^2

7. Sensitivity Analysis

A sensitivity analysis is undertaken on the HKT hydropower system. LCIA result sensitivity is explored in the key areas of component life spans, transportation, annual power output, and the “soft” design approach.

7.1 Component life spans

Estimation of the lifetimes of system components are dependent on issues of local climate, equipment quality and source, design philosophy, installation robustness, stakeholder involvement, and the capacity for local maintenance and repair. In order to account for this in the HKT hydropower LCA, sensitivity analyses are undertaken in which scheme component life spans are uniformly adjusted from half of modelled component life spans (50%) to two times the expected life spans (200%). Variation in selected scheme component life spans is presented for each scenario in Table 7.1.

Table 7.1 Variation in selected scheme component life spans for each sensitivity scenarios

	Replacement after n (years)		
Scheme Component Replacement	**Baseline**	**Lifespan 50%**	**Lifespan 200%**
Bearing and capacitor replacement - incl transpo	0.5	0.25	1
Penstock, Weir, Transmission, Distribution	20	10	40
Turbine(Pump and Motor) - incl transpo	5	2.5	10
Electronics - incl transpo	5	2.5	10

Sensitivity of GWP and PED to the variation of component life spans is shown in Figure 7.1 and Figure 7.2.

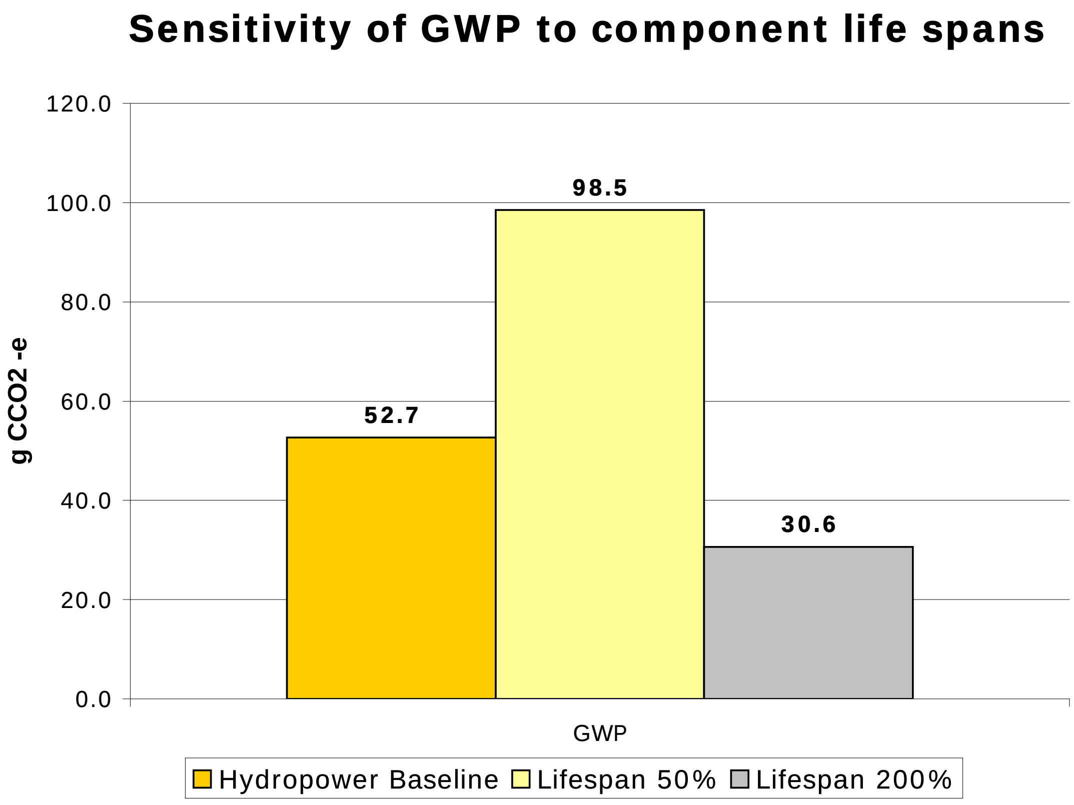

Figure 7.1 Sensitivity of GWP to component life spans

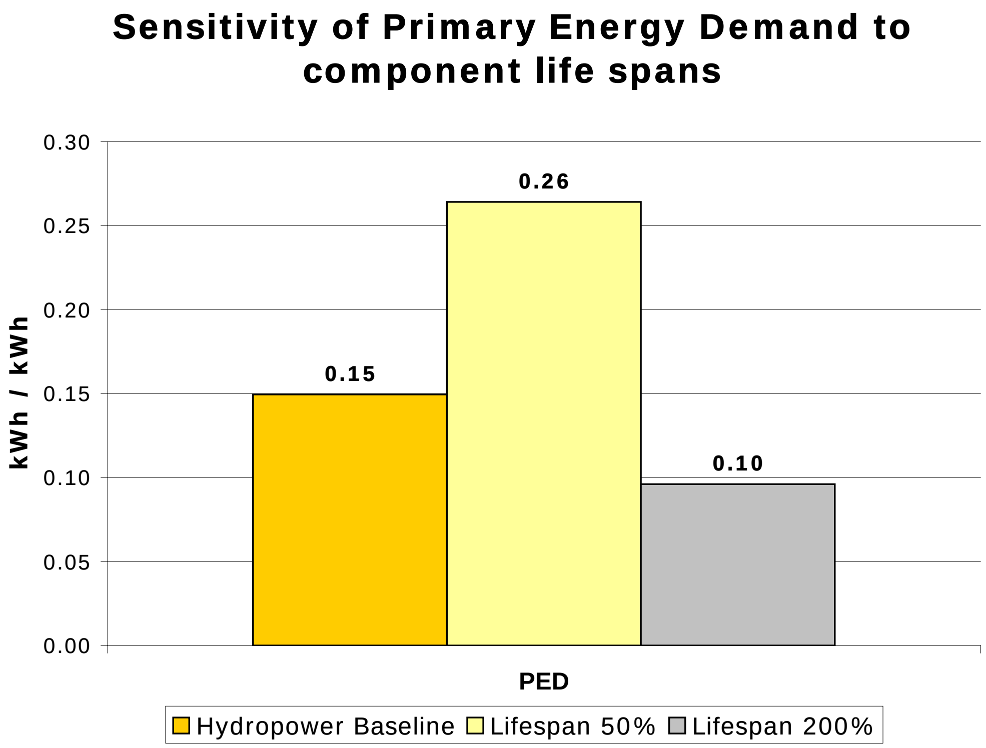

Figure 7.2 Sensitivity of Primary Energy Demand to component life spans

Both GWP and PED increase by over 76% when component life spans halve. GWP and PED are less affected by an increase in component life spans but still show more than a 35% reduction when life spans double. While the relationship described here is not strictly linear when applied to the results in all LCIA categories, if all else is held constant, uniformly doubling component life spans decreases LCIA results per kWh by between 35% and 50%. Uniformly halving scheme component life spans increases LCIA results per kWh by between 76% and 100%.

Table 7.2 compares LCIA results for the halved lifespan system with modelled electrification alternatives. With the exception of ODP, LCIA results for a hydropower system with halved component life spans are still lower by at least a factor of three per kWh than either Thai grid connection or diesel systems.

Table 7.2 Comparison of LCIA results for halved component lifespan system with alternative electrification options using multiples of baseline system's LCIA results

Category or Indicator	Hydropower Baseline	HKT 7kVA Diesel Mini Grid for 0.4L/kWh	HKT Connection to Thai Power Grid	Lifespan 50%
ADP	1	34	23	1.8
AP	1	8	29	1.9
EP	1	12	14	1.8
GWP	1	26	18.5	1.9
ODP	1	1.2	4	2.0
POCP	1	8	22	1.9
PED	1	35	24	1.8

7.2 System performance

In the following analyses, annual output is varied from a robust system operating at full capacity (3kW and 95% annual availability) to an underperforming system operating at 320W and 85% annual availability (this is the same as 1.6kW at 17% annual availability)[23]. The baseline model produces 1.6kW for 85% of the year. Results of this sensitivity analysis on lifetime GWP are shown in Figure 7.3.

[23] The underperforming system operating characteristics were estimated from two periods of logger data taken during 2006 and 2007 at HKT. A summary of this data is available in Appendix L. Analysis showed that the system was only generating 14-17% of expected output.

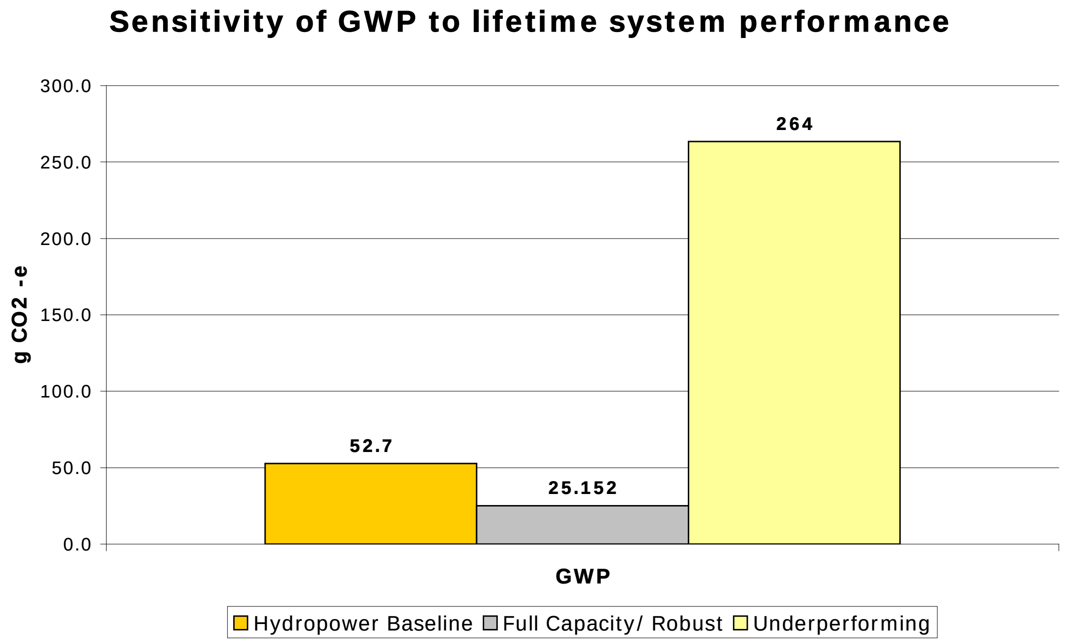

Figure 7.3 Sensitivity of GWP to lifetime system performance

Trends for the rest of the LCIA impact categories are directly linear and increase by a multiple of five for the underperforming system. Environmental impacts decrease by just under half for the robust and full capacity system.

Table 7.3 compares LCIA results for the underperforming system with modelled electrification alternatives. With the exception of ODP, LCIA results for the underperforming system are lower per kWh than either Thai grid connection or diesel systems.

Table 7.3 Comparison of LCIA results for underperforming system with alternative electrification options using multiples of baseline system's LCIA results

Category or Indicator	Hydropower Baseline	HKT 7kVA Diesel Mini Grid for 0.4L/kWh	HKT Connection to Thai Power Grid	Underperforming
ADP	1	34	23	5
AP	1	8	29	5
EP	1	12	14	5
GWP	1	26	18.5	5
ODP	1	1.2	4	5
POCP	1	8	22	5
PED	1	35	24	5

7.3 "Soft approach"

This analysis inspects the effect of varying amounts of concrete used in the installation.[24] Concrete use is varied from no concrete use to four times the amount in the baselines study. Results of the sensitivity analysis are presented in Figure 7.4.

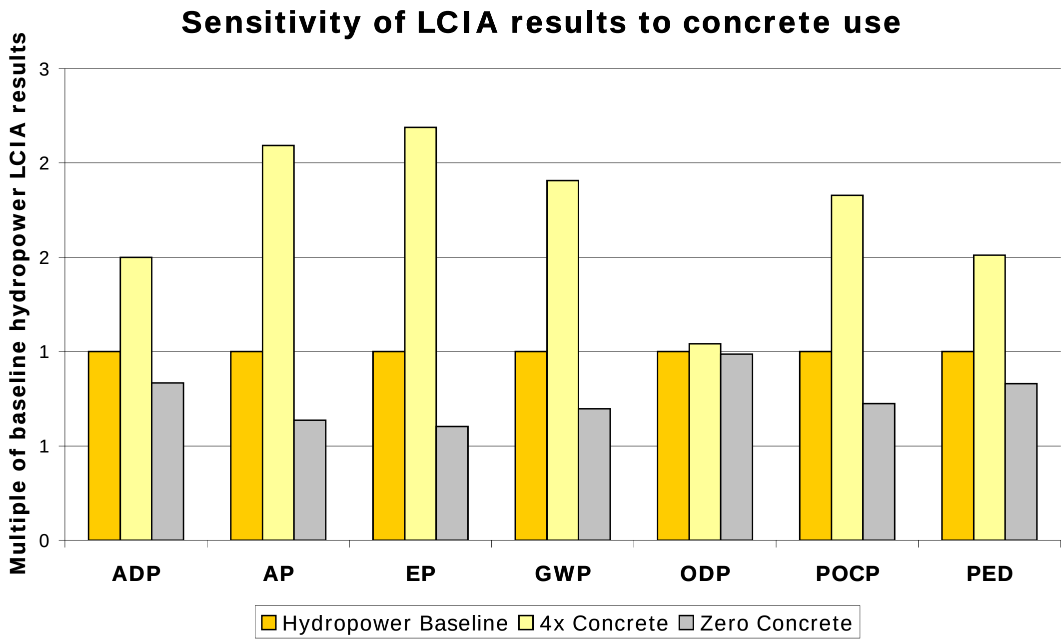

Figure 7.4 Sensitivity of LCIA results to concrete use

Sensitivity analysis results show that the "soft approach" used at HKT greatly reduces overall environmental impact and that an even further reduction in concrete use would potentially provide more environmental benefits. The

[24] HKT replaced its locally sourced wooden power poles with concrete power poles in ~2008. It was uncertain whether this move was motivated by local forestry officials or component longevity concerns.

potential interplay of this sensitivity analysis with results from other sensitivity analysis such as system robustness is discussed in the next chapter.

Table 7.4 compares LCIA results for the 4x system with modelled electrification alternatives. In all categories LCIA results for the system with four times the concrete are lower per kWh than either Thai grid connection or diesel systems.

Table 7.4 Comparison of LCIA results for 4x cement system with alternative electrification options using multiples of baseline system's LCIA results

Category or Indicator	Hydropower Baseline	HKT 7kVA Diesel Mini Grid for 0.4L/kWh	HKT Connection to Thai Power Grid	4x Concrete
ADP	1	34	23	1.5
AP	1	8	29	2.1
EP	1	12	14	2.2
GWP	1	26	18.5	1.9
ODP	1	1.2	4	1.0
POCP	1	8	22	1.8
PED	1	35	24	1.5

7.4 Transportation

Transportation of each piece of equipment in the HKT hydropower system contributes a varying percentage of the overall LCIA results. For example, transportation of the turbine from Tokyo to Bangkok by cargo ship comprises four percent of the GWP impact resulting from the turbine in HKT hydropower system. Transportation from Bangkok to HKT by cargo truck represents another four percent of overall GWP results. In order to determine the effect of transportation on overall HKT hydropower system results, the following analysis compares the sensitivity of LCIA results to three different transportation scenarios.

Scenario one eliminates all international transportation. This approximates the regional production of all scheme materials and equipment in Thailand (using foreign processes) and requires 300 km (50 km local roads, 250 km highway) of regional transportation in a diesel truck.

Scenario two eliminates international travel and reduces regional transportation distances to 30 km (30 km local roads). This assumes all materials and equipment are manufactured (using foreign processes) in regional Bangkok.

Scenario three assumes equipment is not manufactured in Bangkok but in the greater SE Asia region. Each finished product is transported an average of 709 km (50 km local roads, 659 km highway) by diesel cargo truck to Bangkok. The chosen distance is the average of a sampling of Thai cities located on Thailand's northern and eastern borders with Burma, Laos and Cambodia.

Distances for all scenarios are shown in Table 7.5 below.

Table 7.5 Transport distances for Thailand regional sensitivity analysis

Scenario	Mode	From	To	Distance (km)	Source
1,2,3	All	International	Bangkok	0	
1	Truck	Regional	Bangkok	300	Estimate
2	Truck	Regional	Bangkok	30	Estimate
3	Truck	Extended	Bangkok	709	Average
(3)	Truck	Bangkok	Chiang Rai	784	(Google & Tele Atlas 2010)
(3)	Truck	Bangkok	Nong Khai	693	(Google & Tele Atlas 2010)
(3)	Truck	Bangkok	Ubon Ratchathani	650	(Google & Tele Atlas 2010)

The sensitivity of LCIA results to the three transportation scenarios is presented in Figure 7.5. Baseline hydropower scheme LCIA results are represented by the tan bars showing 100% impact in each LCIA impact category.

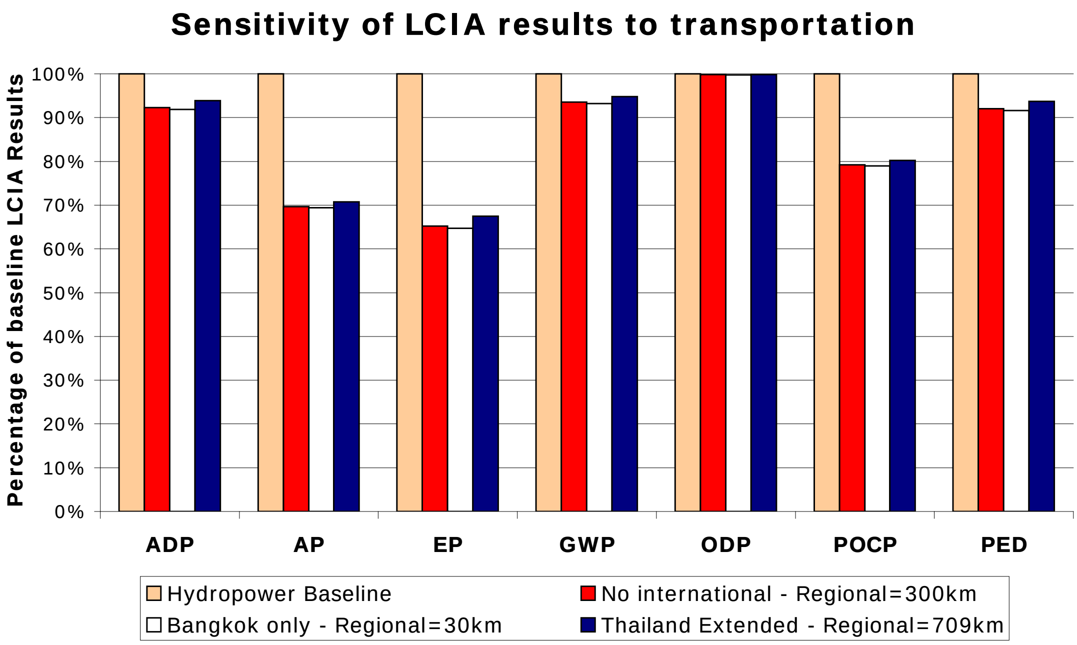

Figure 7.5 Sensitivity of LCIA results to transportation

The sensitivity analysis shows that Thailand based production of all materials (red and white) can reduce environmental impacts by over 20% in AP, EP and POCP categories. ADP, GWP and PED see an five to nine percent reduction through the transportation changes associated with Thailand based manufacturing. ODP which arises mainly from aluminium production is largely unaffected by transportation differences. Pushing production to and beyond the land borders of Thailand and into regional SE Asia (blue) only marginally deducts from the overall environmental gains made by the elimination of long distance international transport (white and red).

7.5 Worst and best case systems

This analysis conflates three of the previous sensitivity analyses into one comparison. In the best case scenario, the system operates robustly at full capacity, contains no cement and has components that last twice their estimated lifespan. In the worst case scenario, the system contains four times the cement, underperforms and system components last half their estimated lifespan. Results of the best and worst case systems are compared with baseline hydropower, diesel system and grid connection systems. The results are presented in Table 7.6.

The baseline system is used as the reference for this table and returns one in every category. All other systems represent multiples of the baseline system.

Table 7.6 Comparison of LCIA results for best and worst case systems with alternative electrification options using multiples of baseline system's LCIA results

Category or Indicator	Hydropower Baseline	HKT 7kVA Diesel Mini Grid for 0.4L/kWh	HKT Connection to Thai Power Grid	Best Case	Worst Case
ADP	1	34	23	0.26	14
AP	1	8	29	0.18	20
EP	1	12	14	0.18	21
GWP	1	26	18.5	0.20	18.2
ODP	1	1.2	4	0.23	11
POCP	1	8	22	0.20	18
PED	1	35	24	0.26	14

Results from the worst case scenario are not meant to reflect reality but define one end of a range of environmental impacts arising from the hydropower system. Should the system exhibit these characteristics in real life, it may be quickly abandoned due to mounting costs, villager frustration and overall disappointment. In such a case overall environmental impacts per kWh would be based on lifetime system production before abandonment and most likely would be much higher than alternatives.

LCIA results for the worst case scenario are mixed. The hydropower system performs worse than alternative systems in some areas and better in others. In ADP, GWP and PED categories, the worst case system still outperforms both diesel and grid system. In EP and ODP categories, the system performs worse than either alternative. An individual comparison with each alternative must be made to determine relative performance in AP and POCP categories.

The best case scenario represents the high end of a range of environmental credentials that are possible from a well designed, "soft" and robust system. The best case system consistently returns reductions in all categories of 73% or better than the baseline. The potential of achieving this goal is discussed in the next chapter.

8. Discussion

8.1 LCIA results compared to model alternatives

While providing the same level of energy availability over a 20 year span, the hydroelectric system holds a clear environmental advantage over diesel and grid connection alternatives. Only when the HKT hydropower system devolves into the worst case scenario (underperforming, four times the concrete and halved component life spans) do its environmental credentials become comparatively questionable. If the HKT hydropower system moves in the direction of the best case scenario, its credentials only improve. This result directly meets a goal of this study.

However, there are limitations on this result. A modelled system is not a real life system. System logger data retrieved from HKT over two short periods in 2006 and 2007 and analysed in Appendix L suggest that HKT system performance trends toward the underperforming system. Cement use is also expected to rise over 20 years as transmission and distribution poles are now 100% concrete. In order to revise the system's environmental credentials for 2010[25], more data would need to be gathered.

LCA results occur in a framework designed for the characteristics and operation of the hydropower system. The hydroelectric system provides power 24 hours a day, but cannot generate more than 1.6kW. No effort is made to account for the relative merits of alternative systems such as the ability to provide more than 1.6kW at any given time, as well as to adjust to peak community use schedules.

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[25] Even with these adjustments the HKT hydropower system is still expected to return overall environmental results superior to the alternative systems. Net cement use will not increase much as 1) changes in the distribution system will affect all modeled systems and 2) some of the cement in the poles will be offset by the 3x reduction in power pole base cement required by the system using wooden poles. LCIA results for the underperforming system can increase by a maximum of 5x. With the exception of ODP, a minimum factor of 7x is needed for LCIA results to match in the two next closest categories.

In an attempt to account for this disparity, the functional unit is designed to compare a total amount of energy available to the villagers over the life span of the system. The comparison of systems using a set quantity of energy over 20 years does not place requirements on when the energy is available, only that it is available at some point. Further efforts to level the playing field for the comparison include the adoption of a higher fuel to electricity conversion figure for the generator than warranted by the literature review, and exclusion of the regional grid distribution network and transmission losses from consideration in the grid connected model. Recognition of the problem of quantitatively comparing hydropower systems with qualitative differences is noted by both Rule et al. (2009) and Gagnon et al. (2002).

The exclusion of changes in land use from formal LCIA results seems to be a common theme in recent industry hydropower LCAs such as Vattenfall (2008b), and recent rural electrification LCA literature such as Gmünder et al. (2010). As land use directly impacts local environments, it is considered an important environmental aspect of rural electrification. An inability to usefully and understandably include the risks of land use change in this LCA limits its usefulness.

Comparison of schemes using approximate and substitute models limits the use of results. Approximate and substitute models are further skewed by process selection based on scarce and anaemic GaBi 4 database documentation.

8.2 Per kWh LCIA results

When the HKT hydropower LCIA results are removed from in-study comparison with alternatives, the results are less clear. LCA standards suggest data be normalized and weighted for better comprehension (Guinee (ed) et al. 2001). LCIA results on an absolute scale lack a point of reference from which they can be understood. What does the HKT hydropower system's Acidification Potential of 0.372 g SO_2-e mean in a Thai context?

While the determination of the HKT hydropower system's absolute LCIA results directly meets a goal of this study, the lack of a Thailand appropriate normalization, limits LCIA result interpretation and presentation. Alsema (2000) points out that available normalizations and weightings have yet to be adjusted for the conditions and situations in developing countries. Gmünder et al. (2010) find the same problem in detailing life cycle environmental impacts in India.

8.3 LCIA results compared to hydropower literature

The direct comparison of this study's LCIA results and the hydropower LCIA results located in literature and detailed in Appendices Q and R is not attempted in this study. Such comparisons would require qualifications and digressions well beyond the scope of this discussion. However, HKT hydropower results tally with a trend observed in the surveyed literature.

Hydropower LCAs note that smaller hydroelectric systems return higher measures of GHGs per kWh than larger systems (Gagnon & van de Vate 1997; Dones *et al.* 2004). Vattenfall (2008b) goes further and suggests that the smaller capacity systems in its inventory have greater impacts per kWh in all LCIA categories.

This study returns a GWP result of 52.7 g CO_2-e /kWh for the HKT hydropower system. This is considerably higher than the 0.576 – 25.6 g CO_2e /kWh GWP range reported for the 300kW to 1001MW capacity hydropower schemes in surveyed literature. After conversion to a uniform metric[26], the HKT hydroelectric scheme returns a PED of 540 kJ /kWh. This is also considerably higher than the 13 – 140 kJ/kWh PED range reported for the 300kW to 1001MW

[26] Appendix Q provides the calculations used to arrive at the primary energy demand figures for each study.

capacity hydropower schemes in surveyed literature. Acidification, ODP, and POCP follow suit providing higher impacts per kWh than all surveyed studies reporting in these categories. This study's LCIA results appear to support the observation that smaller hydropower systems have higher impacts per kWh than larger systems.

Eutrophication is the only impact category where the 3kW HKT system shows a better environmental performance per kWh when compared to the reviewed studies. The one study that listed a higher Eutrophication value per kWh, and thus a worse performance, was Vattenfall (2008b). Reasons for this anomaly are uncertain although when compared to HKT results the difference is speculated to arise from the large amount of reservoir area represented in the Vattenfall study. Reasons for divergence from Eutrophication results in older literature is again unknown but speculated to arise from the application of more rigorous and standardized accounting practices than older studies.

With the exception of Eutrophication, and recognizing the limitations of comparing results across studies, the much smaller HKT hydropower system returns consistently higher LCIA results per kWh than the much larger capacity hydropower systems appearing in surveyed literature.
Direct comparison of the LCIA results presented in Appendix P is complicated by the diversity of study characteristics presented in Appendix O. Even if similar labels and units are provided, study differences muddle comparisons.

- Functional unit accounting - All LCA literature surveyed uses 1kWh of electrical energy as the functional unit, but studies vary in where that 1kWh is measured and whether that 1kWh includes consideration of system losses.
- System boundaries and exclusions - Most LCA documentation surveyed explicitly includes scheme creation, transportation, and operation and

maintenance. However decommissioning, recycling, switchyards, biomass decomposition and lubricants are not uniformly excluded or included in surveyed LCA literature.

- Highly variable site specific conditions - Literature suggests that even when provided with a hydropower system's capacity, location and type it is still hard to estimate environmental impacts. Highly variable site specific conditions are the ultimate determiner in a hydropower scheme's impact profile (IEA 2002; Pehnt 2006; Varun et al. 2009).
- Standards used – ISO LCA standards only began to appear in the late 1990s. In 2002, the IEA (2002, 3) doubted "if there currently are any complete LCI on electricity generation that complies with ISO 14040, because the standard was established only recently". More recent hydropower LCAs such as Rule et al. (2009) and Vattenfall (2008) directly reference ISO 1404x series standards. Other recent reports on hydropower LCAs such as Pehnt (2006) are less clear about their adherence to standards.
- LCIA reporting - LCIA results do not use the same characterization method and focus on different environmental impacts.

8.4 LCIA results compared to rural electrification literature

LCIA results for the HKT hydropower system are consistently better, with lower environmental impacts per kWh than all rural electrification systems in the surveyed literature. Rural electrification systems assessed in literature include centralized solar PV, grid connection, a 7.5kVA generator running on biodiesel, a 7.5kVA generator running on diesel (Gmünder et al. 2010), two different solar home systems, a grid connected battery charging system and a 6kVA diesel generator (Alsema 2000). A summary of the LCIA results reported in surveyed literature can be found in Appendix R.

The direct comparison of this study's results and the results located in rural electrification literature is fraught with many of the same complications detailed in the previous subsection. Community scale hydropower's comparative advantage needs to be qualified by a description of the full characteristics of each system detailed in surveyed rural electrification LCA literature.

A particular note for cautious comparison is sounded by differences in the LCIA results obtained for the similarly sized diesel generators in each study. Although GWP and PED are within a factor of one (still not very comforting), absolute values for all other impact categories are either not reported on or off by a factor of at least 5.

8.5 Improving environmental performance

Sensitivity analyses suggest that the environmental performance of the HKT hydropower scheme can be further improved by:

- increasing component life spans;
- improving system robustness;
- increasing power generation;
- reducing concrete input, and;
- sourcing all materials from Thailand.

The design and construction of similarly situated hydropower systems can be informed by sensitivity analysis results. This directly meets a goal of this study. However the benefits arising from each of these actions depend on the manner in which change is implemented. The system wide effects of changing a single aspect of the system also need to be considered and understood.

For example, removing cement use from the system can reduce GWP potential by 25%. However, if the reduction in cement makes the system less robust and decreases system performance significantly, net system GWP per kWh could actually rise. Conversely, if a doubling in the amount of cement used in the scheme pushes system performance toward optimum operation, net GWP has the potential to decrease.

Such comparisons can only be taken so far using an LCA process unrepresentative of Thailand and a model that may not represent local Thai manufacturing conditions. Gmünder et al. (2010) also note this problem. Their study calls for LCI data and LCA methods appropriate to India. Any further modelling of the HKT system and discussion of improving its environmental performance requires local LCI data to be included in the model and LCA methods to be adjusted for application to Thailand.

8.6 Application and implementation of LCA in rural electrification

ISO 14040 (1998) relates that LCA may not be appropriate in settings where the economic and social impacts of a service system are of central importance. Rural electrification is one such setting (Khennas et al. 2000; Greacen 2004; UNDP 2003). While not of central importance, it would be hard to argue that the environmental impacts of rural electrification do not matter. The UNDP recognizes the importance of "the use of low cost, low-emission technologies in developing countries", (UNDP 2003, 126). The environmental impacts of the rural electrification options for villages such as HKT need to be accounted for and understood alongside economic and social considerations.

This study represents a first step towards useful environmental input into many areas of rural electrification decision making. System designers can use this report's sensitivity results to lower the overall environmental impact of future systems. Planners can use HKT LCA results to make more environmentally informed decisions in the specification of rural electrification strategy. Policy makers can use HKT LCA results to guide policy design towards the support of low impact environmental technologies such as community scale hydropower. This result directly meets a goal of this study.

In order to be fully accessible to decision makers, the environmental benefits of a rural electrification system need to be integrated with social and economic considerations. Gmünder et al. (2010) concur.

8.7 Application of LCA to Thailand

This study's application of LCA to Thailand uncovers some important observations. Discussion of the observations below directly meets a goal of this study.

Local industries and communities receive limited benefits from results that are not representative of native Thai systems. Opportunities to identify areas for reductions in environmental impacts are hampered by the use of LCI data and representing foreign manufacturing conditions and values.

A model built to circumvent the lack of Thai LCI data does not allow for the accurate geographic location of impacts. LCIA results for the HKT hydropower system detail overall impacts but do not address where and when they are occurring. For example, GWP results reported in this study miss the fact that, as modelled and ignoring transportation in Thailand, nearly all of the 52.7 g CO2-e per kWh the system produces occurs outside of Thailand and before system installation.

It is unknown if the results presented as part of this study's LCIA focus on locally and culturally relevant environmental impacts or describe conditions in a manner that is understandable to Thai audiences. The lack of locally designed, agreed upon and widely accessible LCA methods, indicators and normalizations hampers the utility of LCA in Thailand.

Limitations in expressing these concepts arise from the relative newness of the author to this field and the author's inability to speak and read Thai. Limitations on these findings ultimately arise from the manner in which solutions to the recognized shortfalls are envisioned and carried out.

9 Conclusion

This study asks whether the HKT 3kW hydroelectric power system has the fewest environmental negatives of equivalent electrification options for the village over a 20 year life span. LCA is iteratively applied to the HKT hydropower scheme in order to answer this question. Cradle to grave modelling covers all relevant equipment, materials and transportation required during the scheme's construction, operation and end of life phases.

The study results in the enumeration of the environmental credentials of the HKT hydropower system and highlights the need to place environmental performance, and LCA itself, in a proper context. Credentials are established though comparison with rural electrification alternatives and sensitivity analyses that allow insight into the basis for credentials.

In the broadest sense, LCA results for the HKT hydropower system are in line with a common trend reported in hydropower LCA literature, namely that smaller hydropower systems have a greater environmental impact per kWh – i.e. perform less well environmentally - than larger systems. Placed within a rural electrification context, however, the HKT hydropower system yields better environmental outcomes than all surveyed alternatives. Sensitivity analyses reveal that only when worst case system design and performance are approached do the environmental credentials of the HKT hydropower system become questionable.

Successful community electrification rests on the locally led adaptation of globally sourced technology to meet the specific environmental, social and economic challenges of rural areas. The further useful application of LCA to rural electrification in Thailand requires similar intervention. Local stakeholder involvement is needed to adapt LCA to rural electrification conditions, collect

Thai specific manufacturing data, normalize results to Thailand and report findings in an appropriate manner for local populations. Undertaken collaboratively with local stakeholders and integrated with additional tools such as life cycle costing, LCA can be an indispensable input to rural electrification decision making in Thailand.

9.1 Recommendations for further study

The iterative nature of LCA and my experience thus far suggests that this LCA study could continue ad infinitum. However in the interest of pragmatism and best use of limited resources, the following recommendations for further study are suggested:

- Collect and fully enumerate Thai LCI data for all involved processes. During data collection collaborate with local stakeholders to ensure LCI collection methodology for Thailand is well documented and appropriate for local conditions.
- Optimize the environmental and LCC design of the HKT hydropower system using the sensitivity analyses in this study as a starting point. Expand insight gained to regional systems and beyond if possible. Undertake LCAs of other systems in rural Thailand and SE Asia to support such work.
- Work with local stakeholders to ensure that proper normalizations and weightings are created for Thailand.
- Work with villagers and local stakeholders on the determination and design of impact characterizations appropriate to rural Thailand. Work with the same villagers and stakeholders to determine the best way to present and make that data comprehensible to local populations.
- Explore the use of other LCA software packages in pursuit of this study's original goal and the further study goals listed here. Global Emission Model for Integrated Systems (GEMIS) software is of particular interest.

Compare and contrast the use of this software with GaBi 4 and other software to pursue developing country and rural electrification LCA.

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Appendix A: Huai Kra Thing village description

Huai Kra Thing village is located in Tak Province, Thailand. Tak Province is one of 76 provinces in Thailand, features large swaths of rugged mountainous terrain and shares a border with Burma's Kayin State (Kawthoolei). While Huai Kra Thing (HKT) can be reached from the capital of Tak, the Thailand/Burma border town of Mae Sot is of more importance as a local hub for HKT residents. HKT is 65k road km from Mae Sot. 61km of the road from Mae Sot consists of a two lane carriageway. From this carriageway, Huai Kra Thing's village centre sits 4km and approximately 400m of elevation (BGET 2006b) down a steep and winding single lane road[27]. Figure A.1 below shows a map of region surrounding HKT.

Figure A.1 Region around HKT with routes from Tak city and Mae Sot (Google & Tele Atlas 2010)

A.1 Village life

The village centre consists of roughly 45 houses containing 230 men, women and children, the majority of which are ethnically Kayin. A charismatic and ritually tattooed village elder with a penchant for Hawaiian shirts and cigars serves as the village headman and de facto judge, foreman and statesman.

27 Which in 2006 consisted of alternating concrete and dirt stretches.

Agriculture is the main occupation of the villagers (KNCE 2007) although entrepreneurs offer a variety of services and goods. Villagers rely on animal husbandry and the wealth of the surrounding forest to meet their remaining subsistence needs.

A.2 Infrastructure, transportation and water

The village road system consists of a single central road allowing access to important community buildings. While the road is mainly dirt, areas prone to mud slides and bogging in rainy season are paved over with concrete. Community oriented structures include a Baptist church, a Catholic church, a primary school, school teacher's quarters, a medical clinic, an open air community meeting centre, and gravity fed water storage silos.

Most villagers own or have access to a motorbike or bicycle. A few own personal vehicles such as 4wd trucks. However, almost all locomotion in the village takes place on foot.

Water is available from a gravity feed water system connected to most household taps. Water enters the gravity feed system roughly 700m from the village's central water storage tanks and flows in blue polyvinyl chloride (PVC) pipe from intake to tanks. Water is then distributed from the tanks to village houses via more blue PVC piping.

A.3 Cooking, lighting and electricity

Wood fires serve as the primary energy source for cooking and lighting for evening socializing. Cooking fires are built in sand pits at the centre of well ventilated kitchens. Open wood and charcoal fires at ground level provide the heat needed to smoke and roast animal meat as well as distil local rice whiskey. The sun is tapped through direct radiation for the drying of village staples such as rice, chillies, bananas and fish. Lighting from fires has been supplemented over the years by candles and electricity. Electricity is supplied by small diesel generators, a wide array of batteries, and government supplied solar home systems[28].

[28] In 2003 the Thai Government announced a rural electrification program aimed at providing a 120W solar home system (SHS) to a large portion of the 290,176 households not connected to the countries grid system. Around 200,000 systems were distributed. A 405 system survey undertaken by BGET in Tak province in 2005-2006 found a 22.5% failure rate within the first year of SHS operation (Lynch et al. 2006). HKT village's solar home systems were part of that survey.

Appendix B: Data Quality Overview high level overview of the GaBi model of the HKT hydropower scheme.

Process Plan	Description	Geographic Coverage	Completeness	Data Quality	Assumptions	Data Sources
Section 1: Weir, intake, canal and settling tank	Civil works that capture river water and ensure penstock has a continual supply of water. Local raw materials, concrete, PVC	Manufactured in RER and RNA - transport to HKT. Sand, rock, wood, bamboo flows harvested /collected locally.	Minor items missing from model (plasticizer, cleanout valve gasket, plastic coloring). Missing manufacturing steps (plastics molding, nail making process, HDPE liner making process)	good	Missing materials and manufacturing steps are of negligible impact (<1% for indivudual flows). No product breakage during transport or process waste during implementation. Substitue and created processes are reasonable approximations. Local raw materials from biomass have zero impact cycle.	GaBi 4 database, msds, industry, project documents
Section 2: Penstock	PVC pipe that takes water from settling tank to turbine, includes penstock support materials (wood, nails, wire, concrete, ...)	Manufactured in RER and RNA - transport to HKT. Sand, rock, wood, bamboo flows harvested /collected locally.	PVC Glue incomplete, Missing manufacturing steps (nails, concrete rings)	good	Missing materials and energy flows are of negligible impact (each is <1% of total mass and energy), no product breakage during transport or process waste during implementation. Substitue and created processes are reasonable approximations. Local raw materials from biomass have zero impact cycle.	GaBi 4 database, msds, industry, project documents
Section 3: Powerhouse, turbine and outflow	Machinery and plumbing that turns pressurized water into electricity, structure protecting that machinery, piping that releases spent water	Manufactured in Japan, RER and RNA - transport to HKT. Sand, rock, wood, bamboo flows harvested /collected locally.	Pump and breaker are missing energy and materials and manufaturing steps. Other section equipment may be rough substitutes (capacitors and LED), missing materials (PVC glue incomplete, blue coloring in PVC pipe), or not included (PTFE tape, knife switch, copper wire, amp meter, volt meter, connection strip, paint, wooden mounting board, mounting screws).	good	Missing materials and energy flows are of negligible impact (each is <1% of total mass and energy), no product breakage during transport or process waste during implementation. Pump materials can be approximated from literature. Substitue and created processes are reasonable approximations. Local raw materials from biomass have zero impact cycle.	GaBi 4 database, msds, industry, project documents, literature
Section 4: Transmission line	Aluminum cable that transmits power produced by turbine to control house. Includes power transmission support infrastructure...poles, insulators, etc.	Manuafactured in RER and RNA - transport to HKT. Sand, rock, wood, bamboo flows harvested/collected locally.	Hard drawing of aluminum wire and process for insulating wire with PVC not included. Using a white glass process as a substitute for ceramic insulator.	good	Missing materials and energy flows are of negligible impact (each is <1% of total mass and energy), no product breakage during transport or process waste during implementation. Substitue and created processes are reasonable approximations. Local raw materials from biomass have zero impact cycle.	GaBi 4 database, msds, industry, project documents
Section 5: Control house and electrical control and conditioning equipment	Electrical equipment that maintains a constant load on the turbine, dispatches power to the village as requested and turns excess energy into waste heat. Includes building and internal structures to house equipment and dump load.	Manufactured in Nepal, RER and RNA - transport to HKT. Sand, rock, wood, bamboo flows harvested /collected locally.	Equipment included in this plan are substitues (IGC components, LED), approximations missing materials and/or manufacturing steps (resistive heating elements, ceramics, transformer, circuit breakers) or both (IGC). Equipment not included (high temp wire, copper wiring, knife switch, amp meter, volt meter, breakers, connection strip, mounting screws).	good	Missing materials and energy flows are of negligible impact (each is <1% of total mass and energy), no product breakage during transport or process waste during implementation. Substitue and created processes are reasonable approximations. Local raw materials from biomass have zero impact cycle. 7kW 'humming bird' IGC is a reasonable approximation for the 3kW IGC used in install.	GaBi 4 database, msds, industry, project documents, literature
Section 6: Distribution	Aluminum cable that transmits power from control house to community buildings. This plan ends at the building cutoff switch and does not include building wiring or appliances.	Manuafactured in RER and RNA - transport to HKT. Sand, rock, wood, bamboo flows harvested/collected locally.	Hard drawing of aluminum wire and process for insulating wire with PVC not included. Using a white glass process as a substitute for ceramic insulator.	good	Missing materials and energy flows are of negligible impact (each is <1% of total mass and energy), no product breakage during transport or process waste during implementation. Substitue and created processes are reasonable approximations. Local raw materials from biomass have zero impact cycle.	GaBi database, msds, industry, project documents

Appendix C: 20 year material list used to model the HKT hydroelectric system

Huai Kra Thing Village Hydro Project			
Bill of Materials:			
Quantity	**Unit**	**Item**	**Replacements over 20 years**
		Penstock	
172	m	Schedule 40 - 4" inch blue PVC for penstock	1
4	can	PVC glue/solvent for penstock	1
3	bags	Bags of dry cement mix for thrust blocks	1
466	kg	Mixers added to dry cement to make wet concrete for penstock	1
15	pce	Local wood support structure for penstock	4
45	pce	Galvanized nails for fastening penstock supports	4
60	m	Bailing wire to tie penstock to stands	4
		Weir and intake	
0.5	bags	Bags of dry cement mix for intake	1
78	kg	Mixers added to dry cement to make wet concrete for weir/intake	1
6	sqm	HDPE tarp used as stream bed liner at weir	1
3	m	Bailing wire to tie plastic mesh filter to bamboo structure	4
100	pce	Woven PP rice bags (purchased not reused) to hold rocks and sand for weir	1
1	sqm	Plastic mesh filter (1cm^2) used to filter debris at intake	1
1250	kg	Locally collected rocks for weir	1
1250	kg	Locally collected sand for weir	1
100	pce	Bamboo twist ties for weir	1
0.5	kg	Woven bamboo filter structure for intake	10
		Settling Tank and Canal	
1.5	bags	Bags of dry cement mix for settling tank	1
233	kg	Mixers added to dry cement to make wet concrete for settling tank	1
23	m	Bailing wire to tie mesh filter and to tie canal to stands	4
1	sqm	Plastic mesh filter (1cm^2) used to filter debris in settling tank	1
0.5	kg	Woven bamboo filter structure for settling tank	10
5	pce	Local wood support structure for canal	4
15	pce	Galvanized nails for fastening canal supports	4
50	m	Schedule 40 - 4" inch blue PVC pipe for canal	1
1	pce	Schedule 40 - 1" blue PVC pipe cleanout valve	1
1	can	PVC glue/solvent for canal	1
3	pce	Concrete rings for settling tank (made off site-purchased whole)	1
		Transmission Line	
1200	m	Aluminum Wire 25sqmm for transmission - sheathed	1
4	bags	Bags of dry cement mix for transmission power pole bases	4
621	kg	Mixers added to dry cement to make wet concrete for transmission line	4
40	pce	Ceramic insulators in aluminium bracket for transmission line	1
80	pce	Galvanized nails for fastening insulator structure to transmission pole	4
80	m	Aluminum wire to provide stress relief for transmission wires at pole - no sheath	1
		Distribution Network (up to house cut off switch)	
1178	m	Aluminum Wire 16sqmm for distribution - sheathed	1
40	pce	Local wood for power distribution poles	4
4	bags	Bags of dry cement mix for distribution power pole bases	4
621	kg	Mixers added to dry cement to make wet concrete for distribution lines	4
47	pce	Ceramic insulators in aluminium bracket for distribution line	1
94	pce	Galvanized nails for fastening insulator structure to distribution pole	4
94	m	Aluminum wire to provide stress relief for distribution wires at pole - no sheath	1

Huai Kra Thing Village Hydro Project			
Bill of Materials:			
Quantity	**Unit**	**Item**	**Replacements over 20 years**
		Power house structure	
4	bags	Bags of dry cement mix for concrete pad for turbine	1
621	kg	Mixers added to dry cement to make wet concrete for power house foundation	1
7	kg	Bamboo walls for powerhouse structure	10
4	kg	Bamboo form and rebar for concrete pad	1
47	m	Local wood for powerhouse structure	4
6.25	sqm	Galvanized steel sheets for powerhouse roofing	1
157	pce	Galvanized nails for fastening powerhouse structure	4
		Outflow from Turbine (Tailrace)	
3	m	Schedule 40 - 6" inch blue PVC pipe for outflow	1
1	pce	Schedule 40 - 4" to 6" male PVC adapter for outflow	1
1	pce	Schedule 40 - 4" inch blue PVC pipe screw adapter for outflow	1
1	pce	Concrete rings for outflow (made off site-purchased whole)	1
		Pump as Turbine	
1	unit	4kW Ebara end suction volute pump with four pole 380V motor	4
2	pce	Schedule 40 - 4" inch blue PVC pipe 45 degree connector for buildup	1
1	pce	Schedule 40 - blue PVC pipe 4" to 3" reducer for buildup	1
5	pce	Schedule 40 - 3" inch blue PVC pipe screw adapter for buildup	1
1	pce	3" bronze gate valve for turbine/penstock buildup	1
1	pce	3" cast iron connector for turbine/penstock buildup	1
4	set	7/16 steel J bolts/nuts/washers for mounting turbine to foundation	1
50	m	Bailing wire to tie down penstock in powerhouse	4
1	pce	Red LED system operating light in powerhouse	4
1	pce	Plasting housing for motor run capacitors and overspeed circuit breaker	1
1	pce	25uF Motor run capacitors (380V)	40
1	pce	50uF Motor run capacitors (380V)	40
1	pce	Single throw two pole breaker (6A) in power house for overspeed	1.33
		Control house structure	
7	kg	Bamboo walls for control house structure	10
46	m	Local wood for control house structure	4
6.25	sqm	Galvanized steel sheets for control house roofing	1
152	pce	Galvanized nails for fastening control house structure	4
		Power Control and Conditioning	
1	pce	Steel ballast box (.25 x .8m locally made)	1
1	pce	Stainless steel electronics box - manufactured regionally	1
1	pce	380 to 230Vac 50Hz Hand wound Power Transformer	4
1	pce	3kW Electric Load Controller (IGC) from Nepal	4
1	pce	Red LED system operating light in control house	4
6	pce	Ceramic holders for resistive heating elements	1
3	pce	23inch long 1kW resistive elements for ballast loads (FeCrAl)	2
2	pce	Single throw two pole breakers (15A and 20A) in control house	1.33

Appendix D: GaBi 4 plans for the HKT hydroelectric system

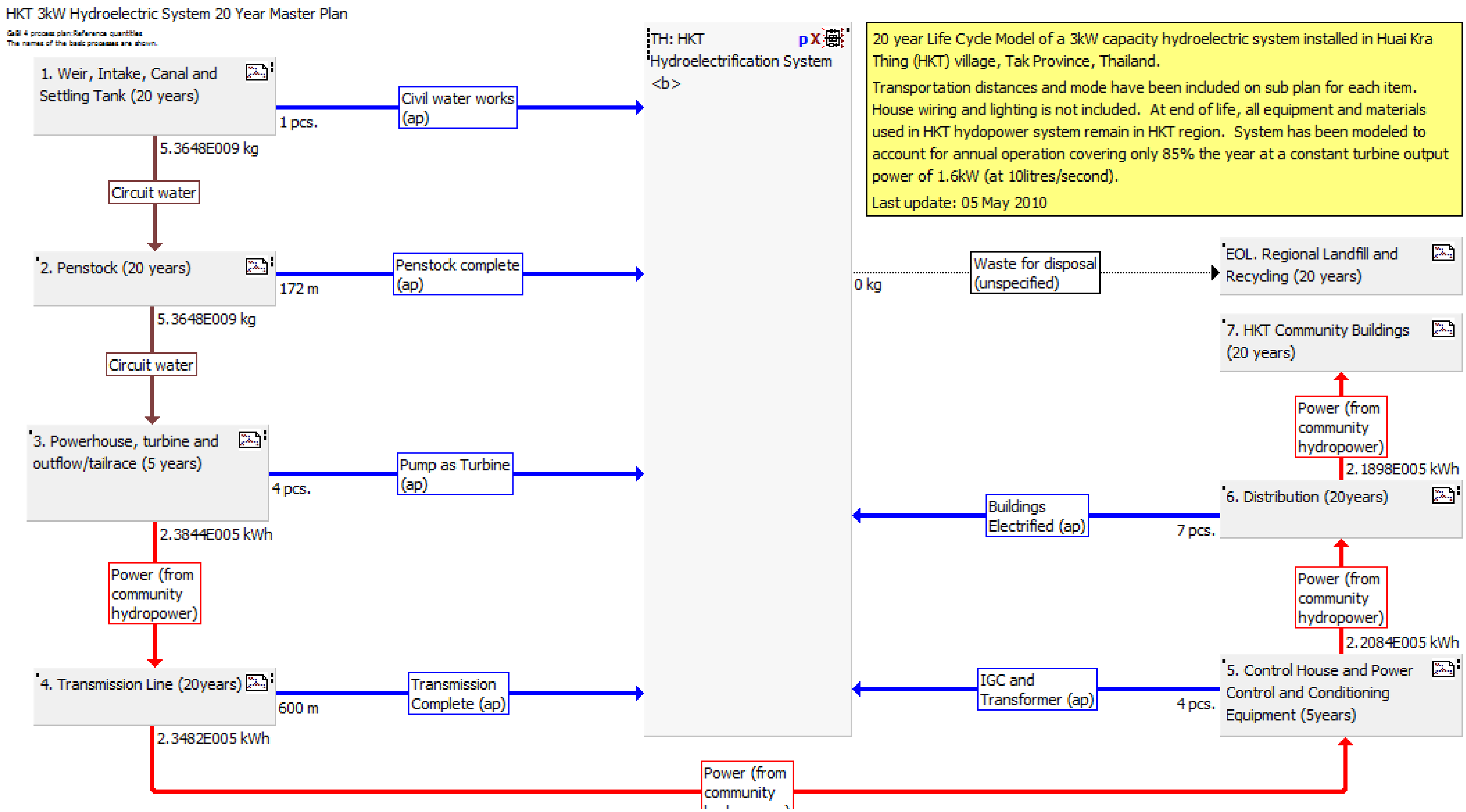


Figure D.1 HKT 3kW Hydroelectric system 20 year master plan central model

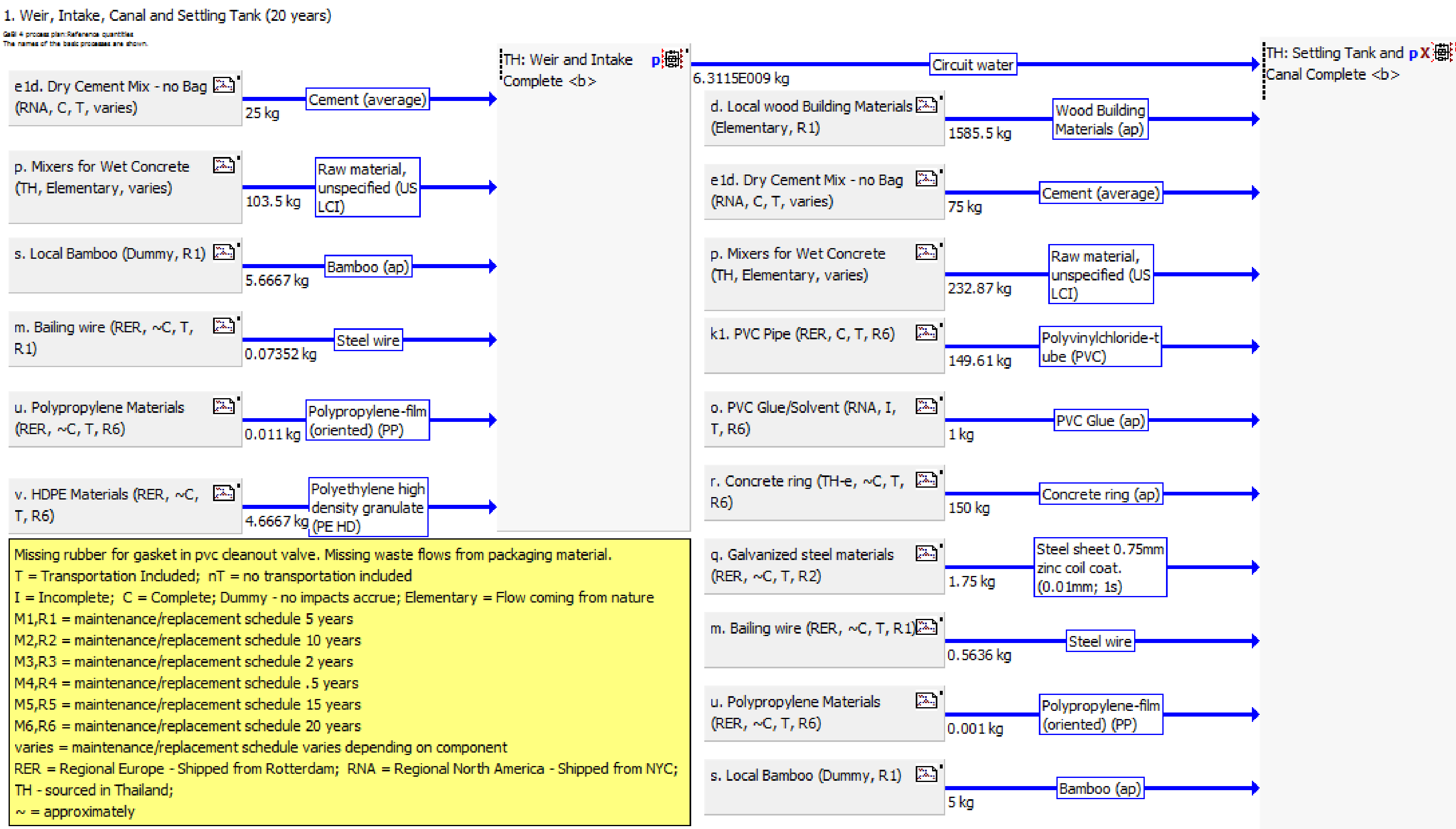


Figure D.2 Weir, Intake, Canal and Settling Tank

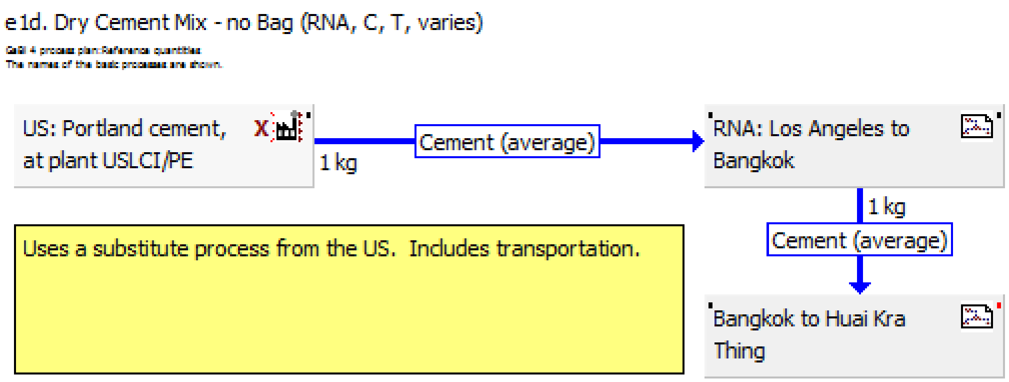


Figure D.3 Dry Cement Mix - no Bag

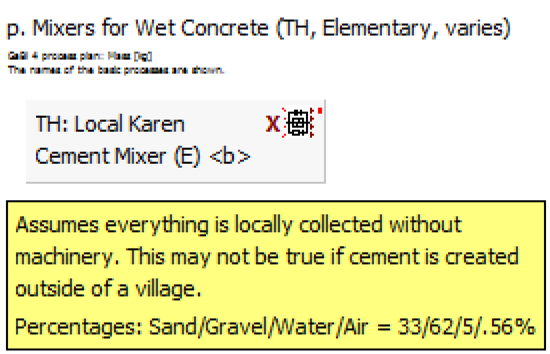


Figure D.4 Mixers for Wet Concrete

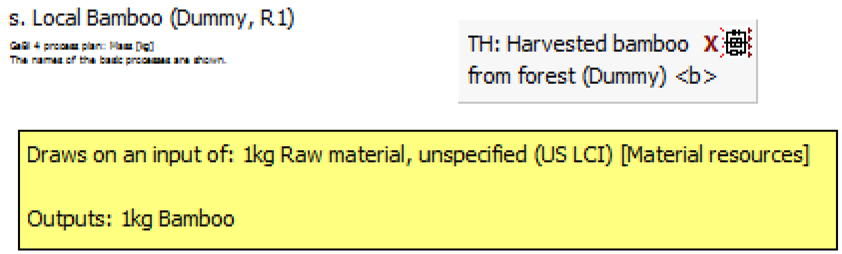


Figure D.5 Local Bamboo

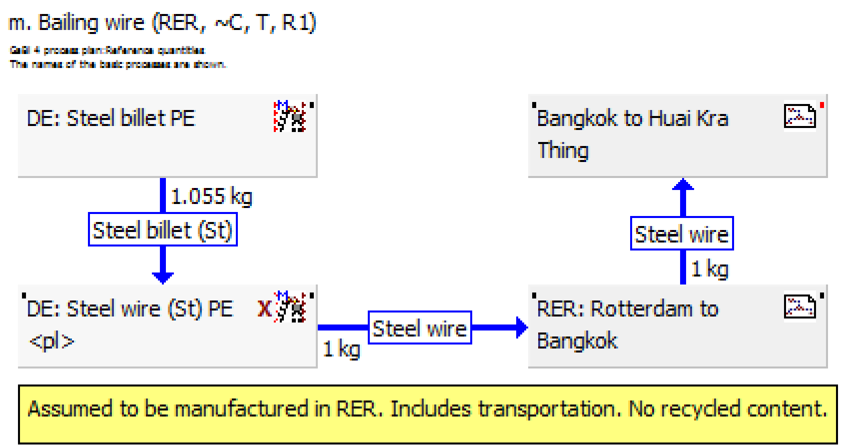


Figure D.6 Bailing wire

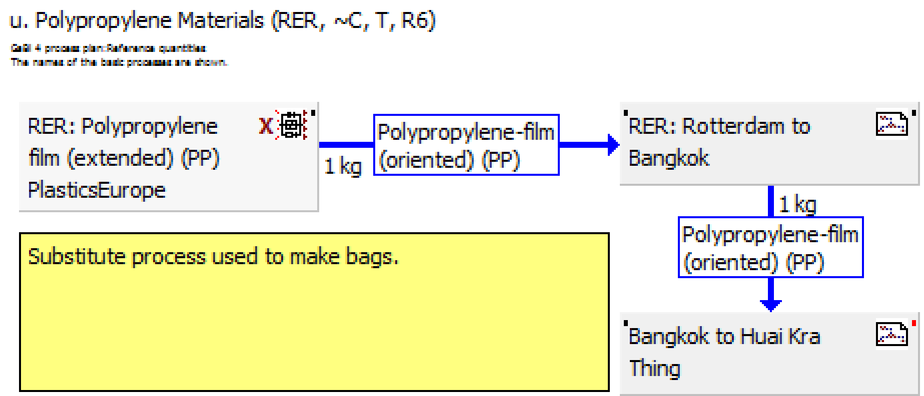


Figure D.7 Polypropylene Materials

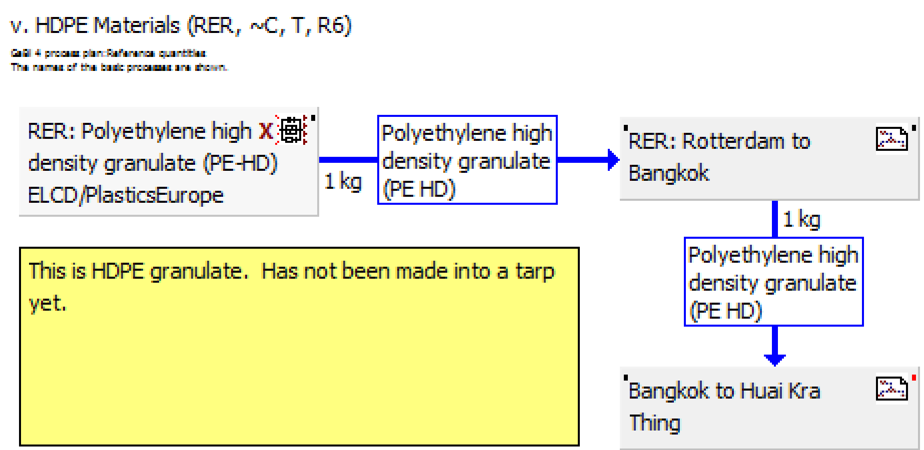


Figure D.8 HDPE Materials

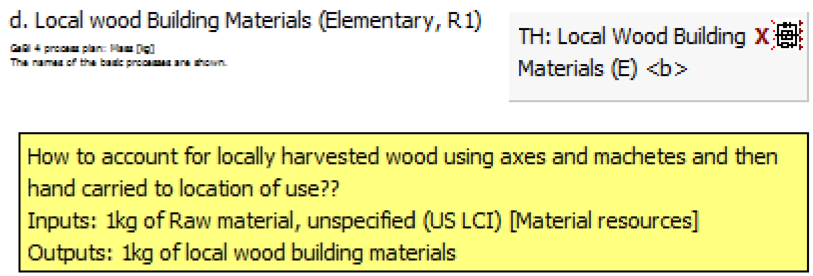


Figure D.9 Local wood Building Materials

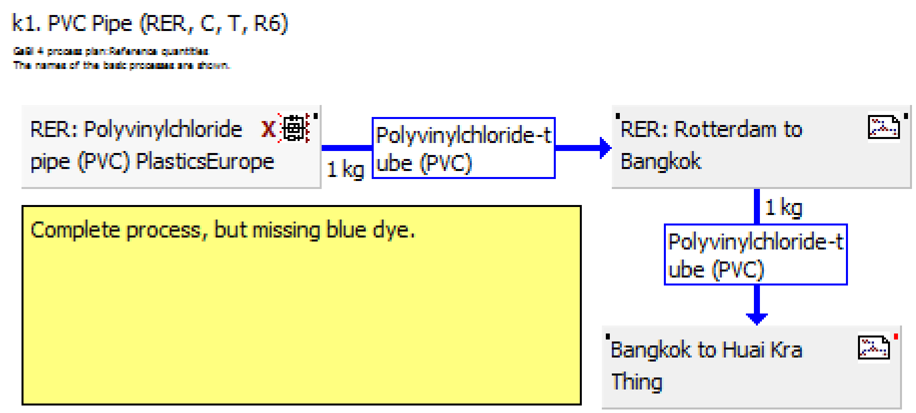


Figure D.10 PVC Pipe

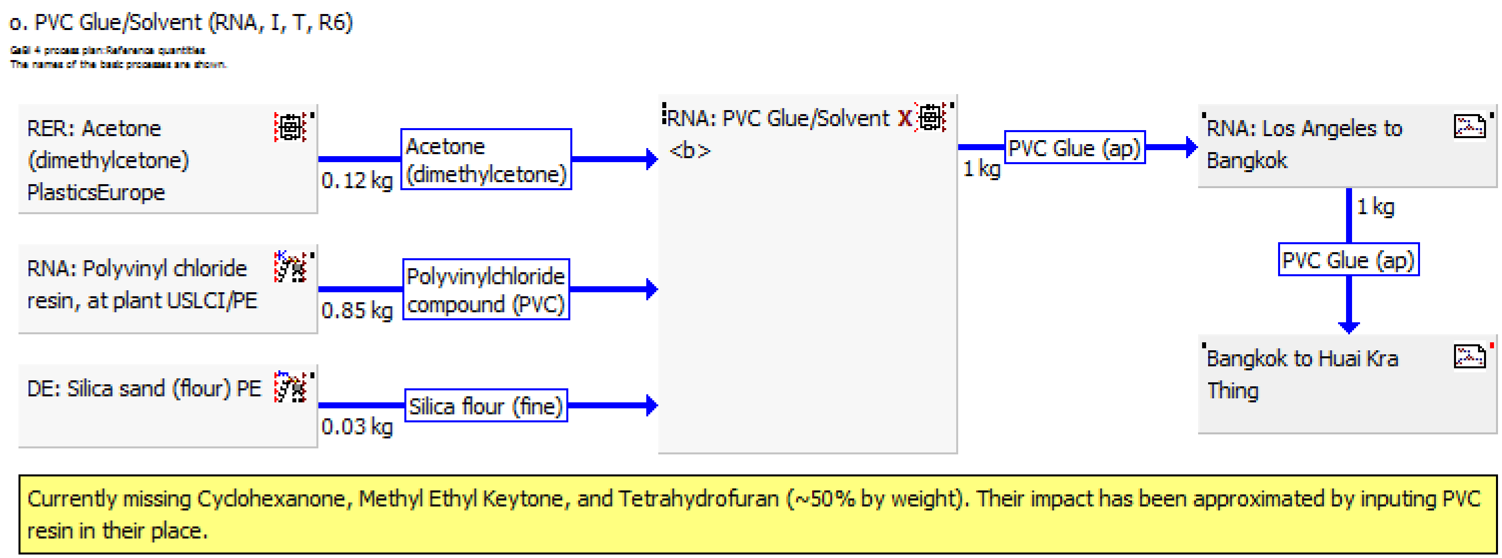


Figure D.11 PVC Glue / Solvent

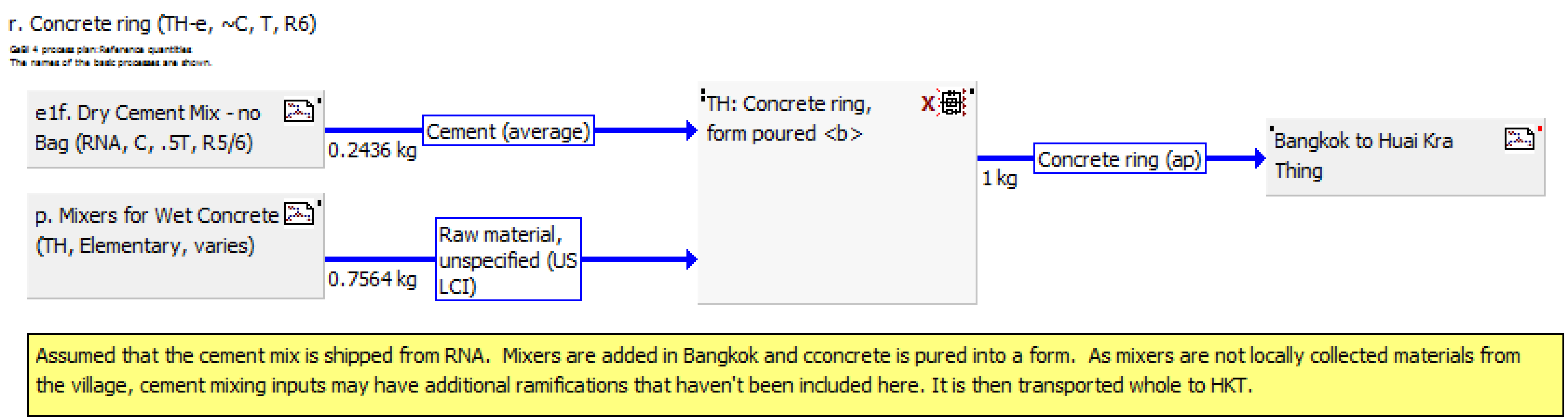


Figure D.12 Concrete ring

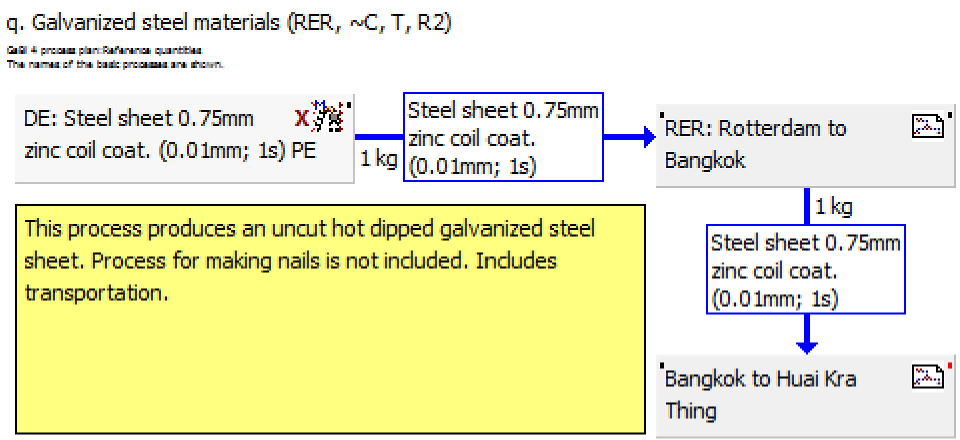


Figure D.13 Galvanized steel materials

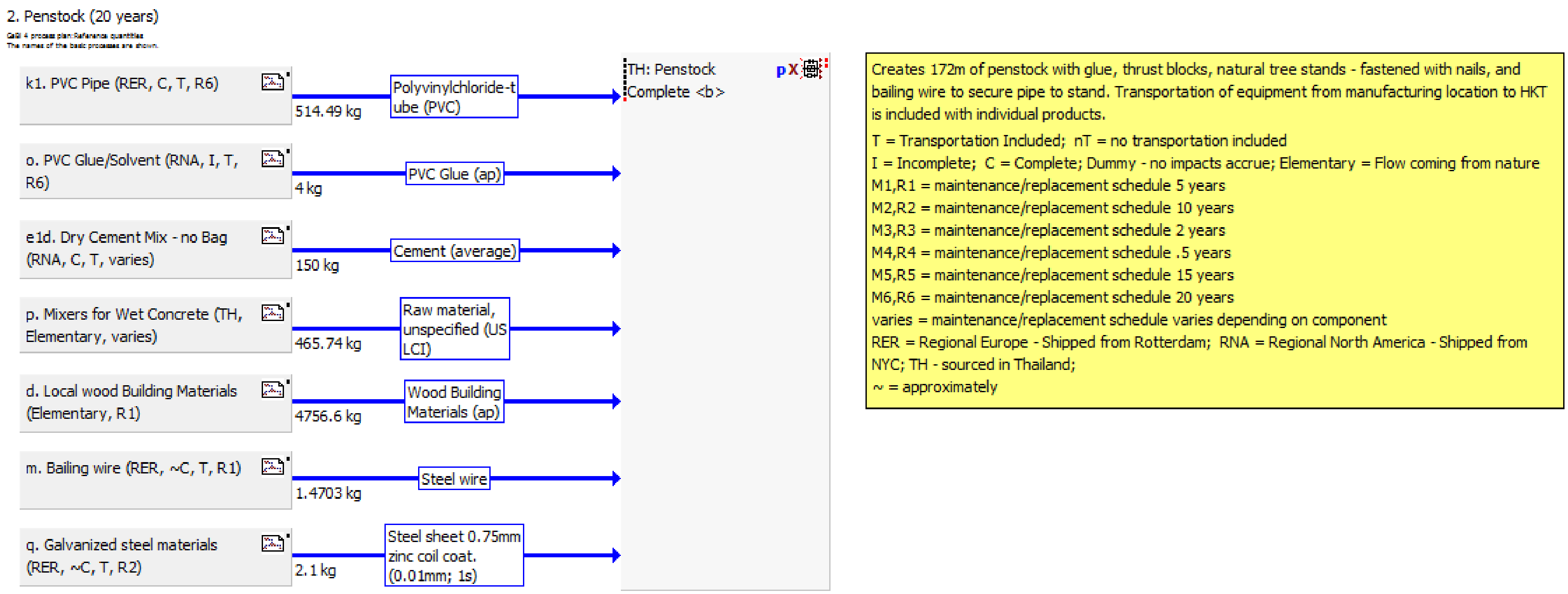


Figure D.14 Penstock

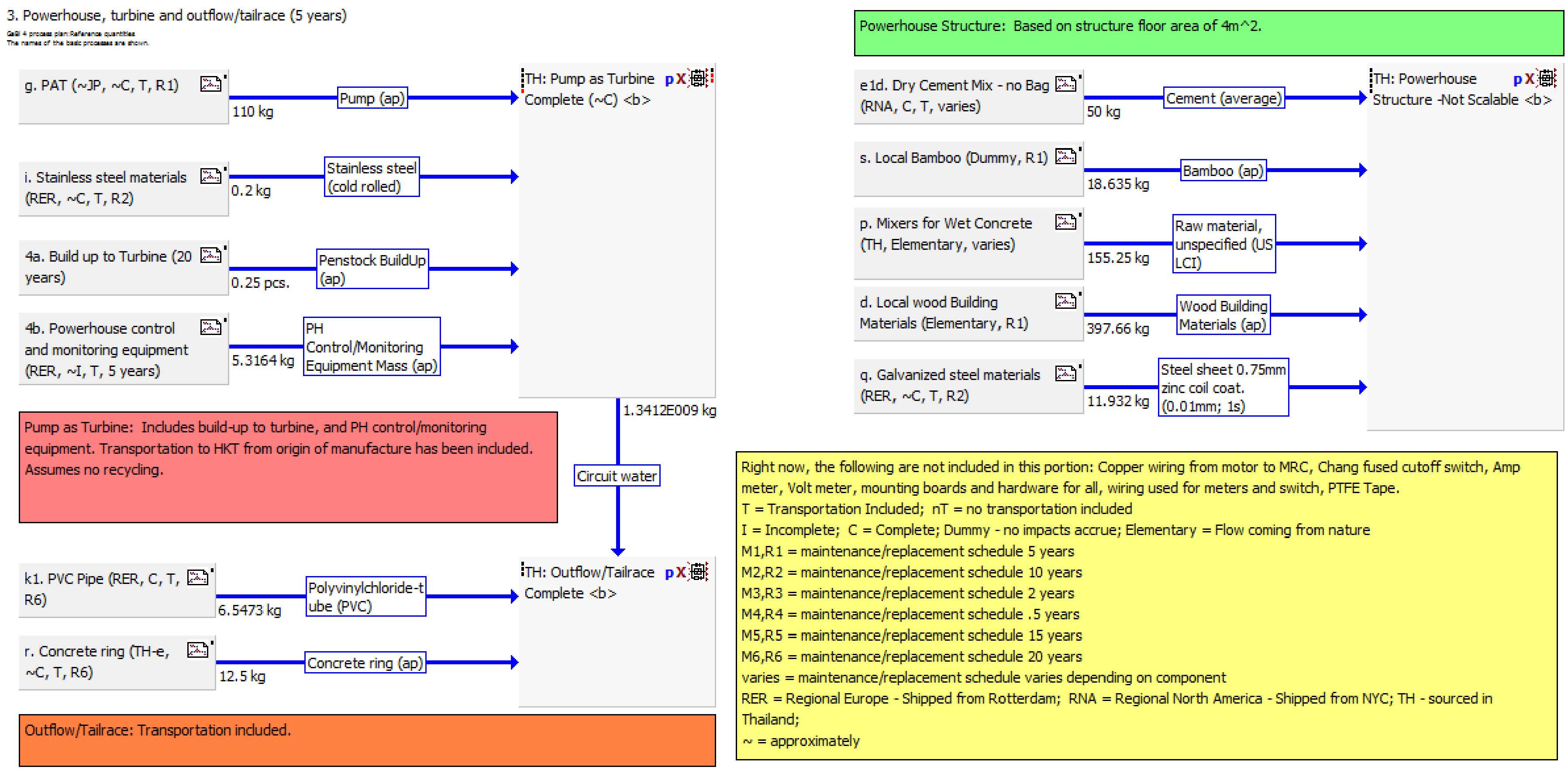


Figure D.15 Powerhouse, turbine and outflow / tailrace

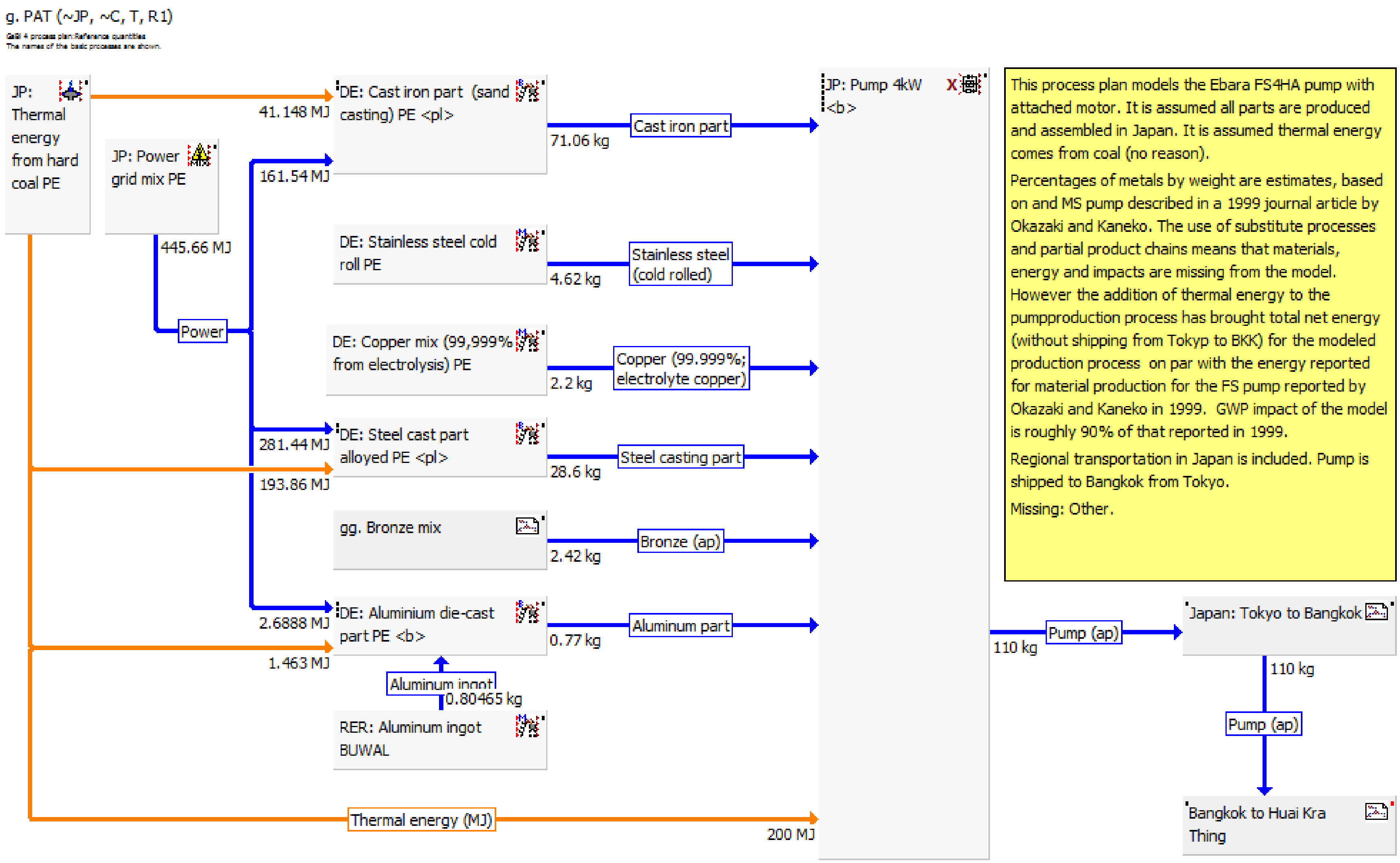


Figure D.16 PAT

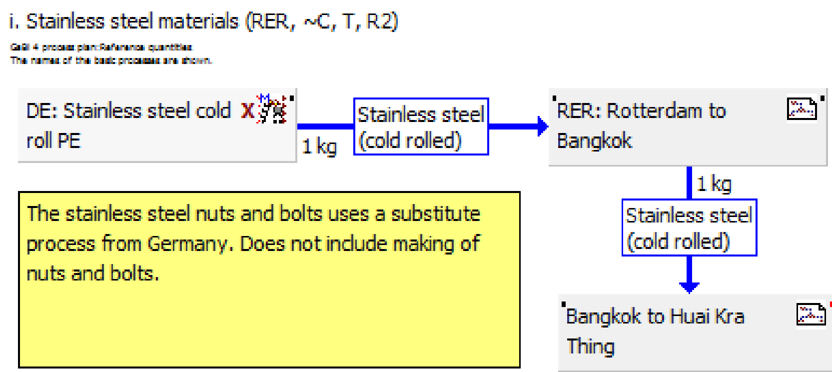


Figure D.17 Stainless steel materials

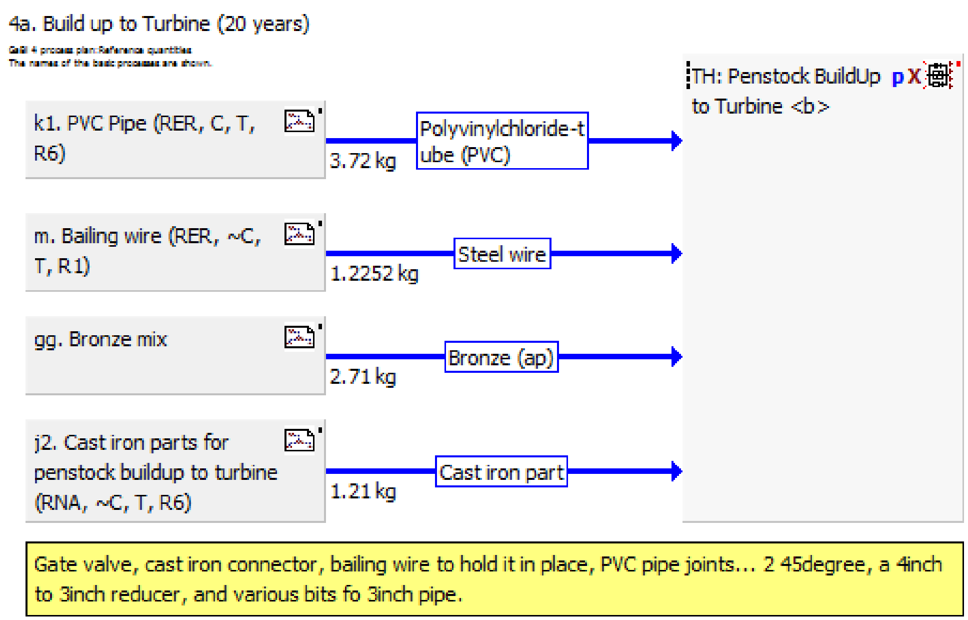


Figure D.18 Build up to Turbine

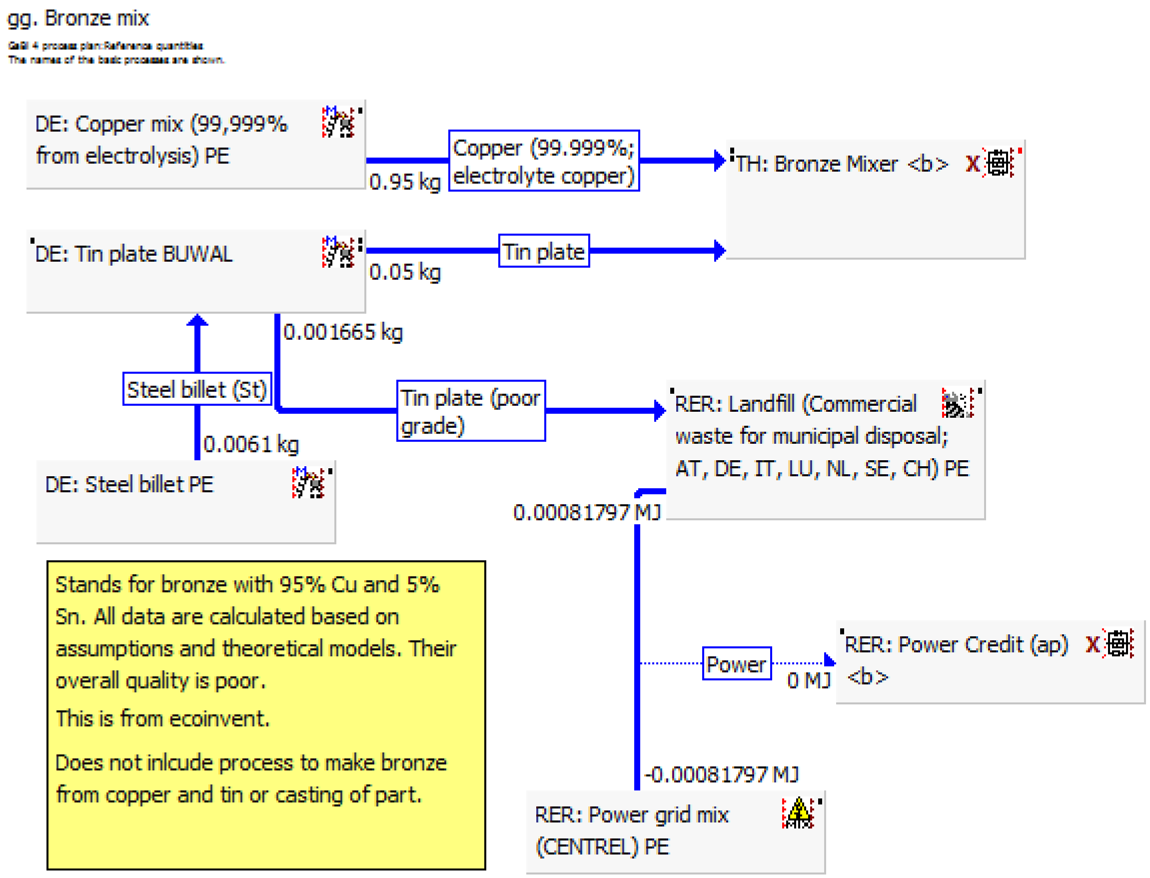


Figure D.19 Bronze mix

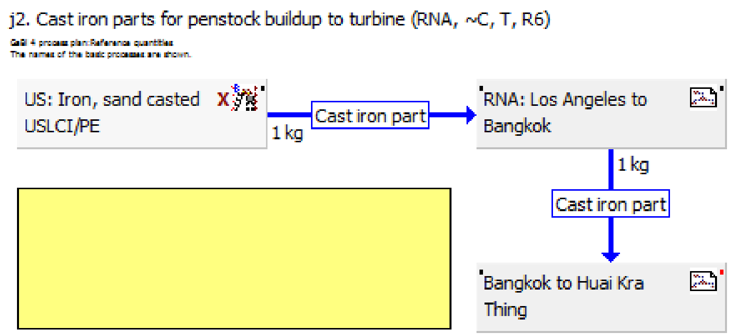


Figure D.20 Cast iron parts for penstock build up to turbine

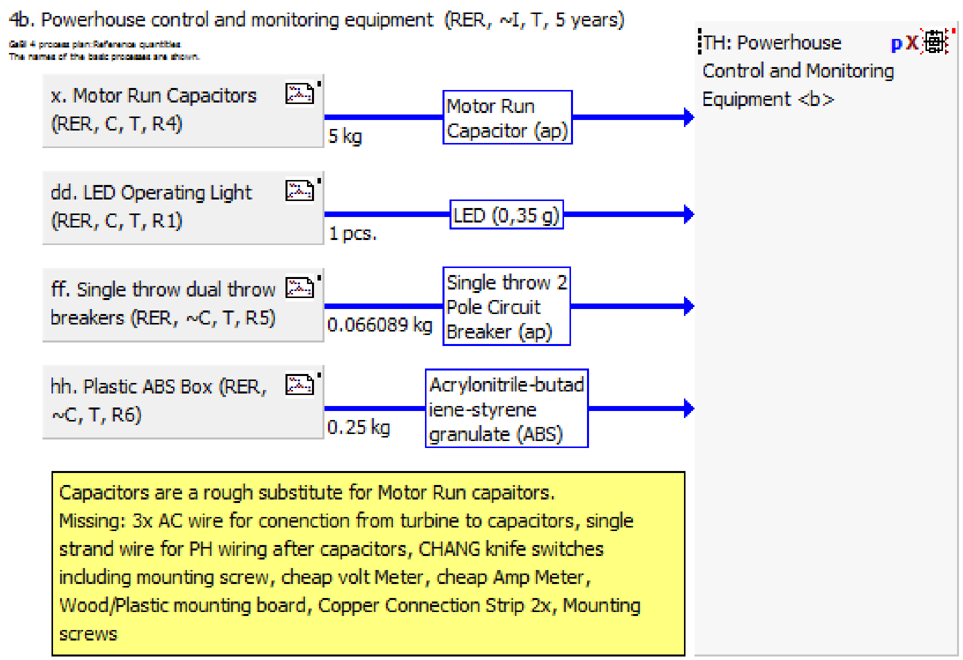


Figure D.21 Powerhouse control and monitoring equipment

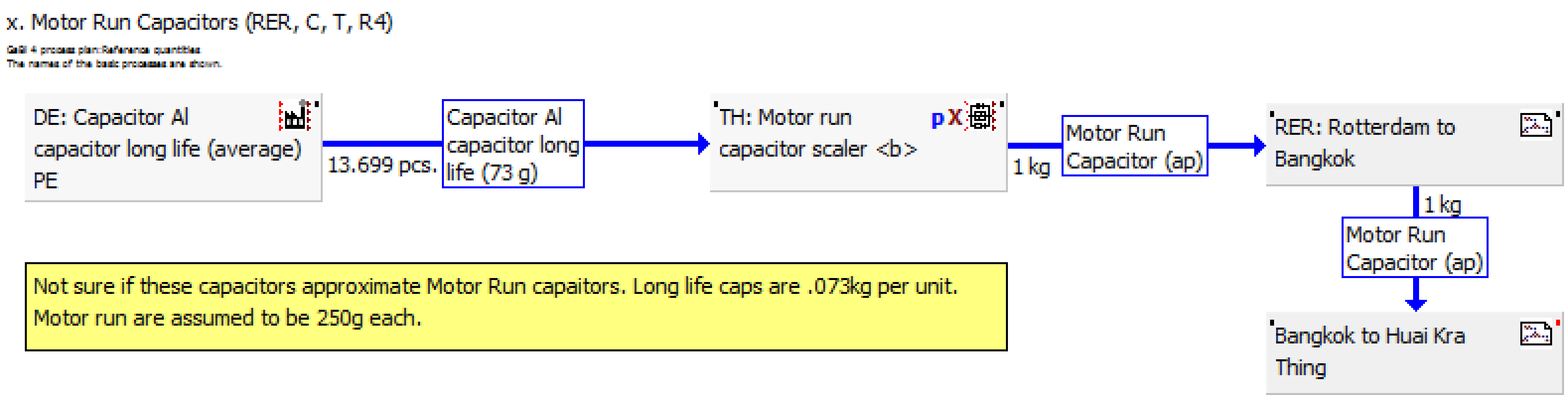


Figure D.22 Motor Run Capacitors

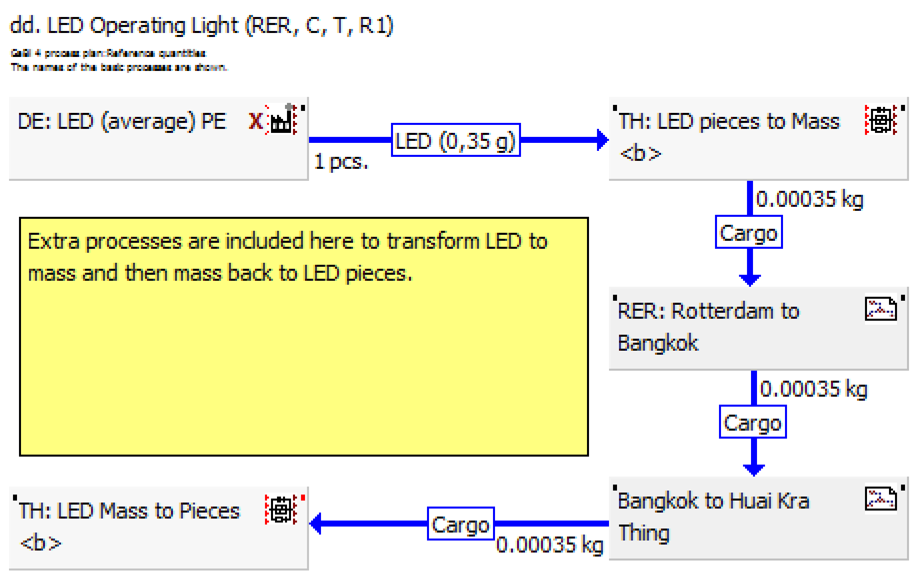


Figure D.23 LED Operating Light

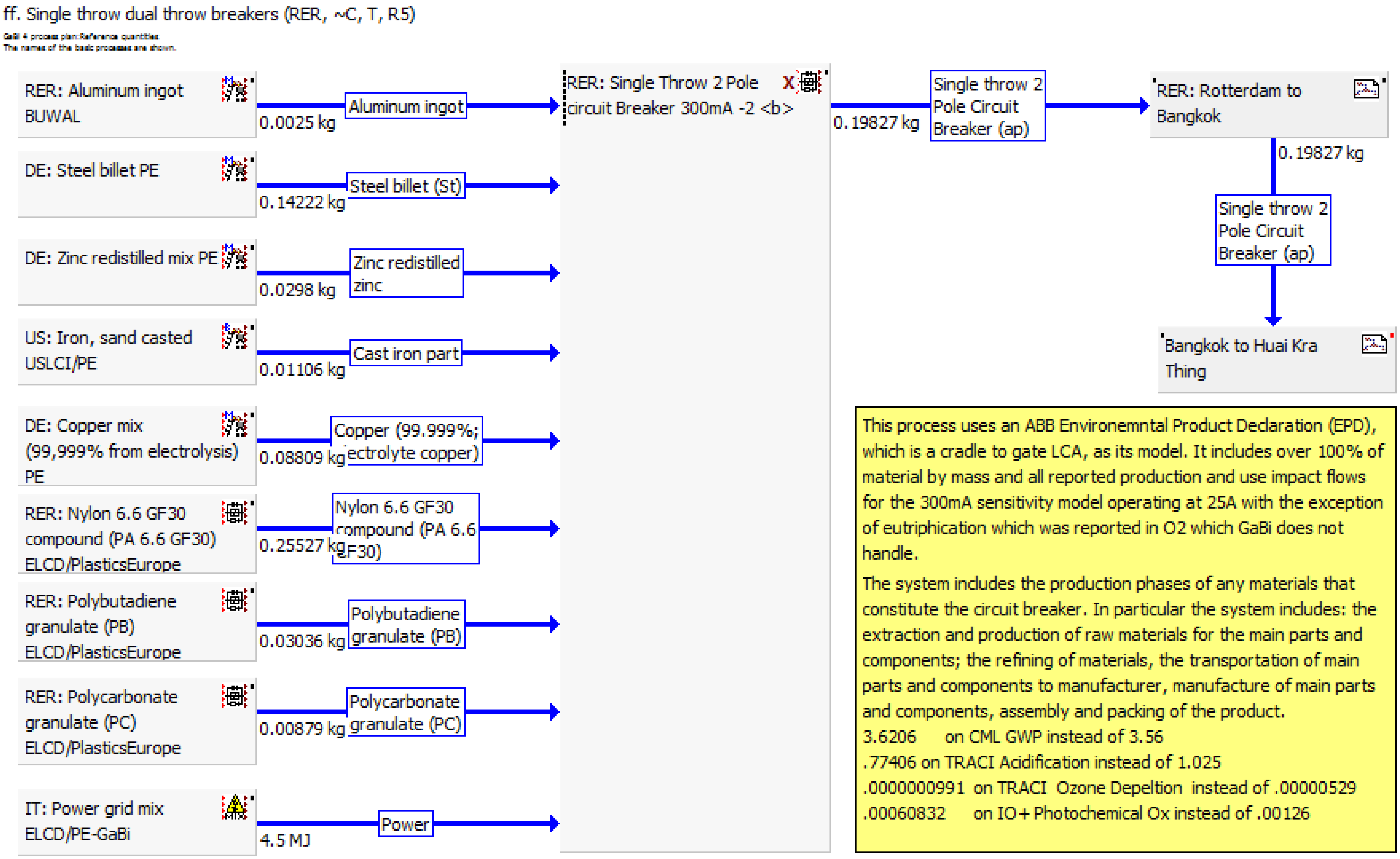


Figure D.24 Single throw dual throw breakers

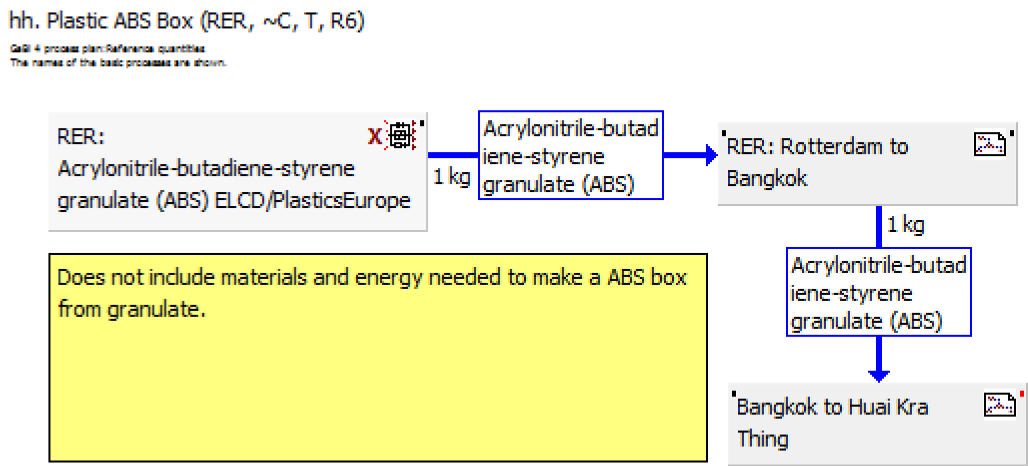


Figure D.25 Plastic ABS Box

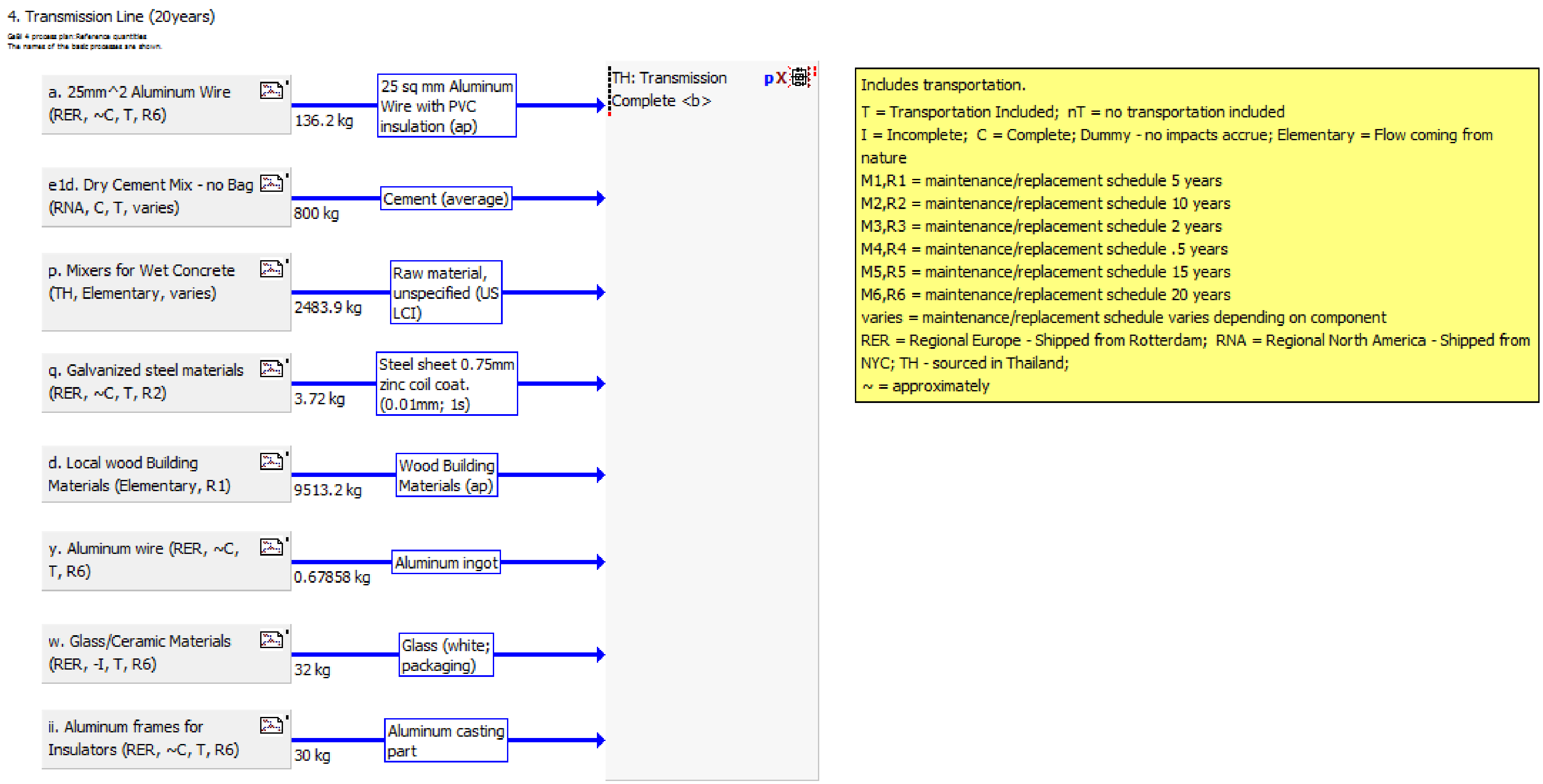


Figure D.26 Transmission Line

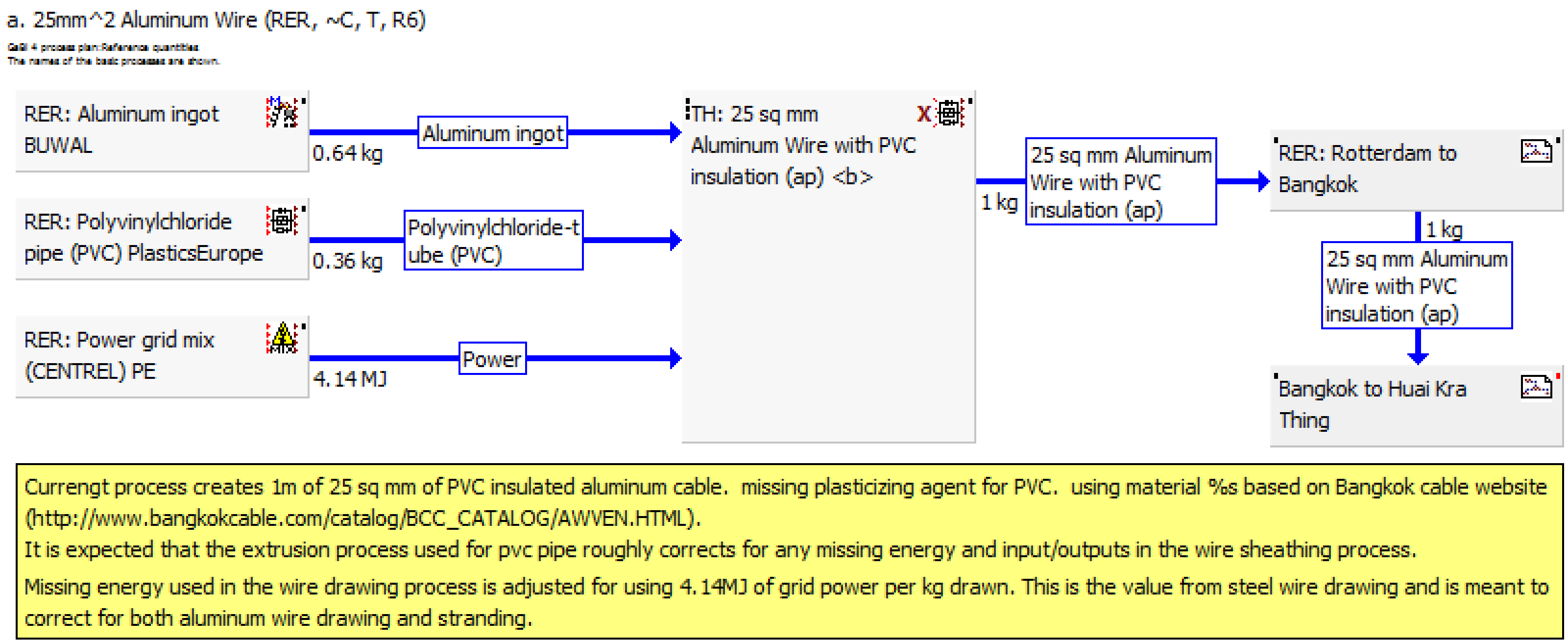


Figure D.27 25mm^2 Aluminium wire

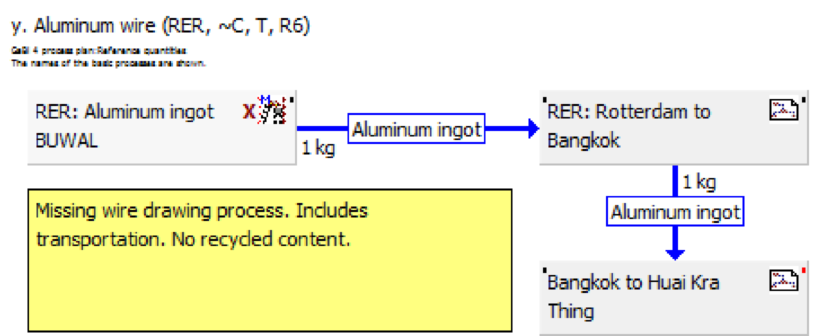


Figure D.28 Aluminium wire

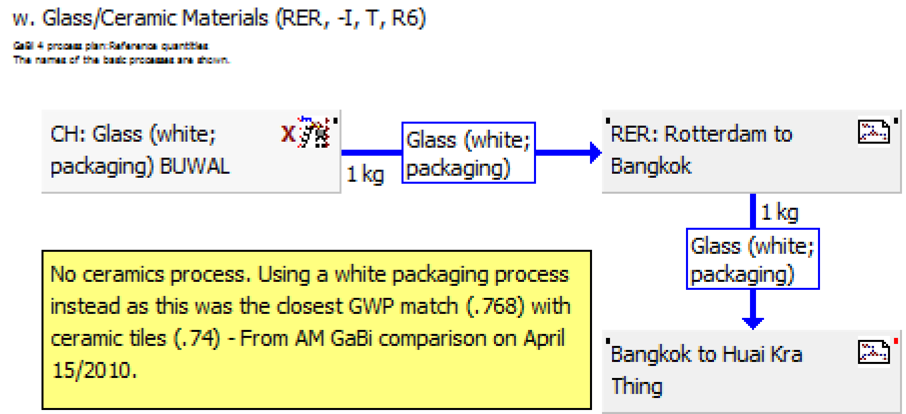


Figure D.29 Glass/Ceramic Materials

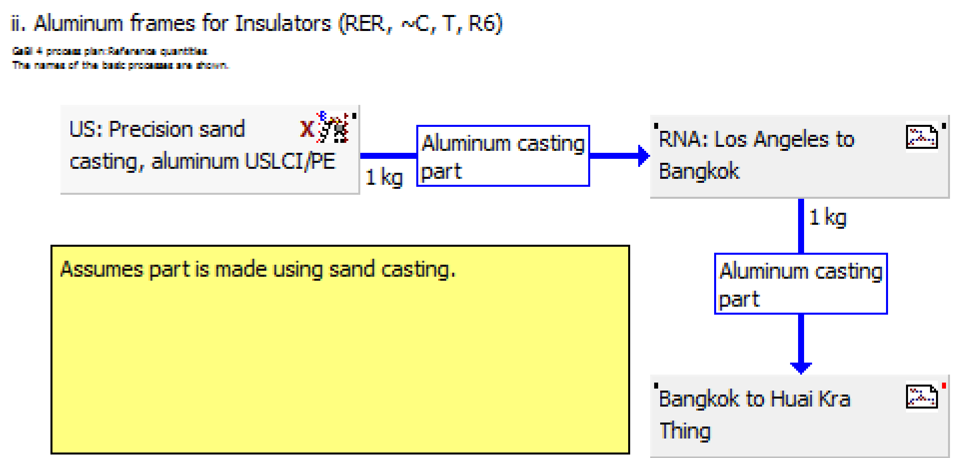


Figure D.30 Aluminium frames for Insulators

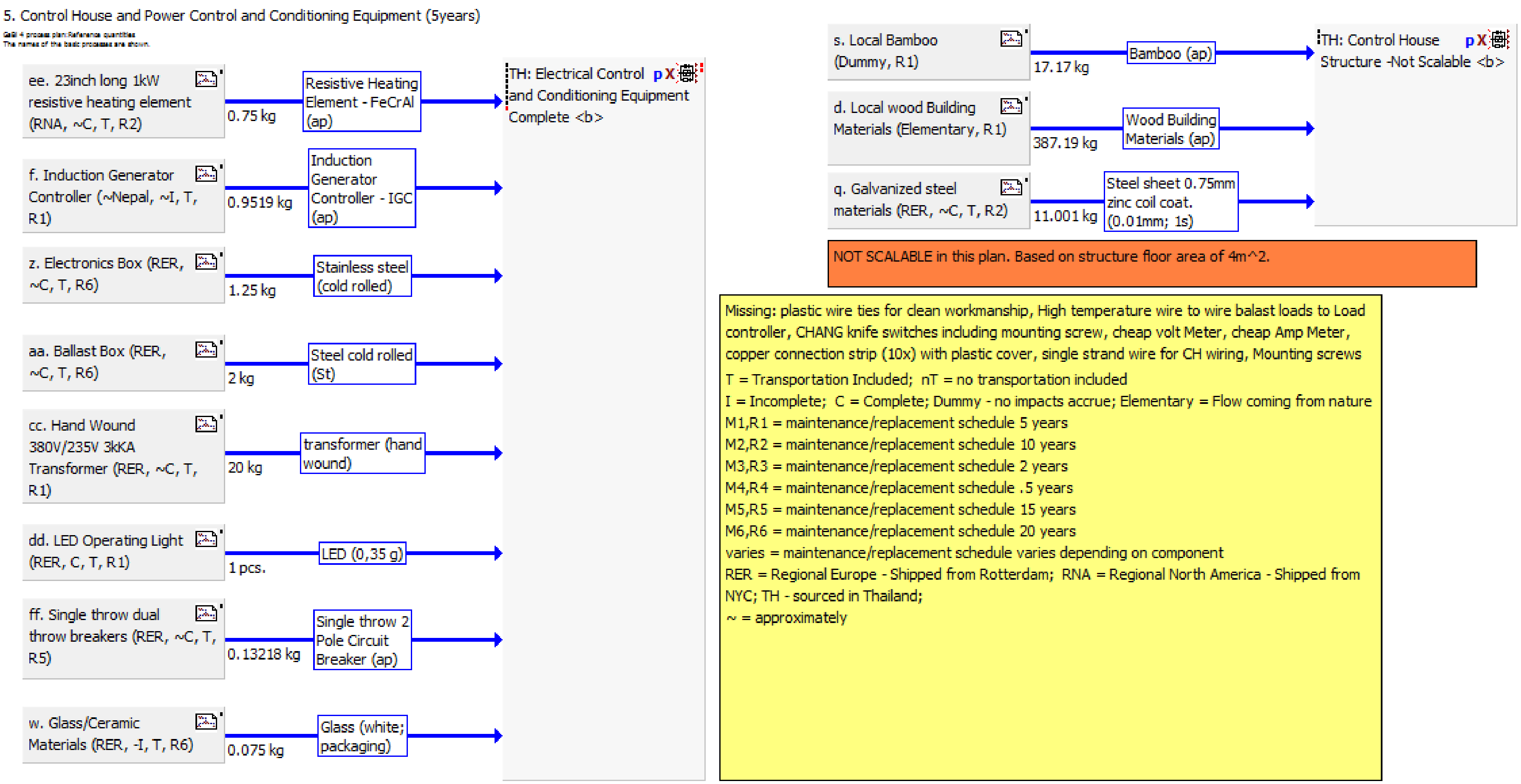


Figure D.31 Control House and Power Control and Conditioning Equipment

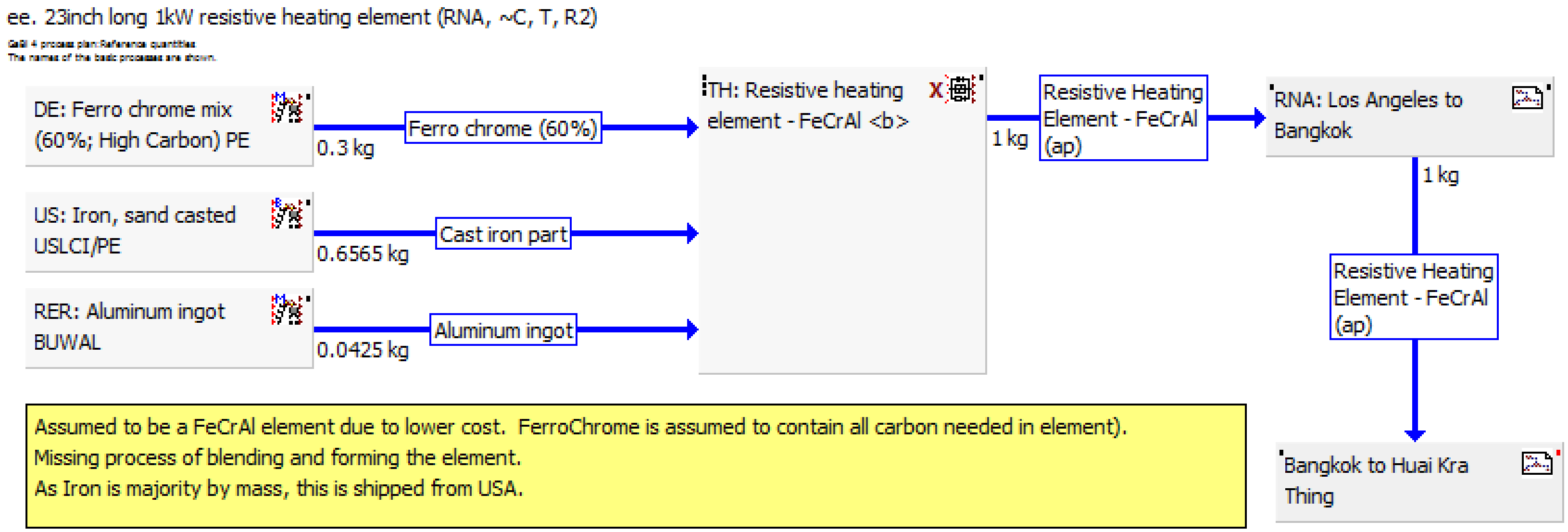


Figure D.32 23inch long 1kW resistive heating element

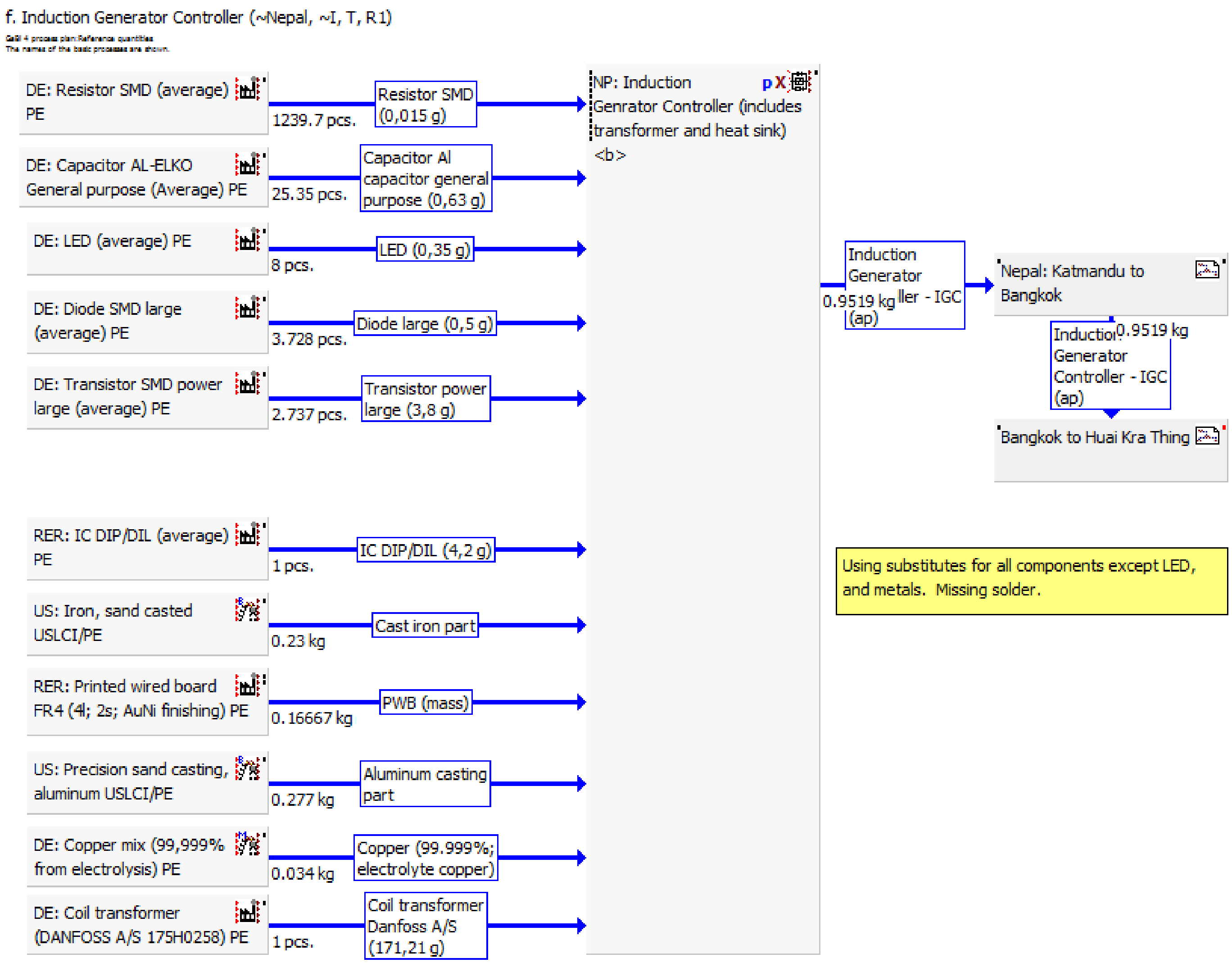


Figure D.33 Induction Generator Controller

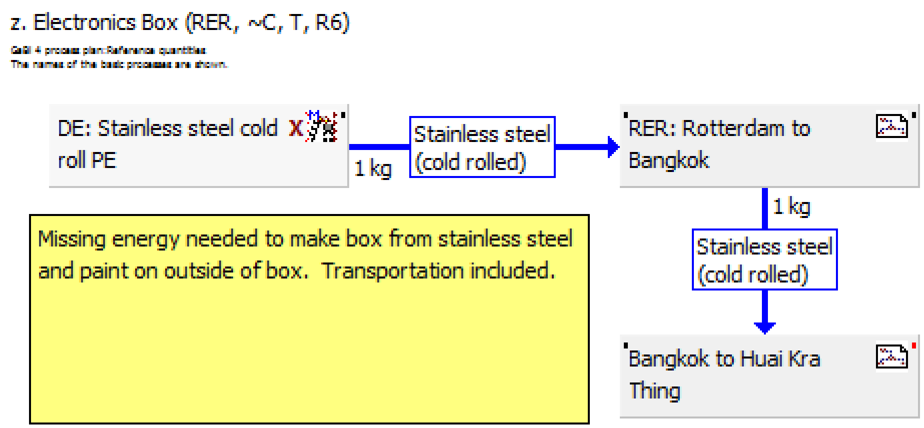


Figure D.34 Electronics Box

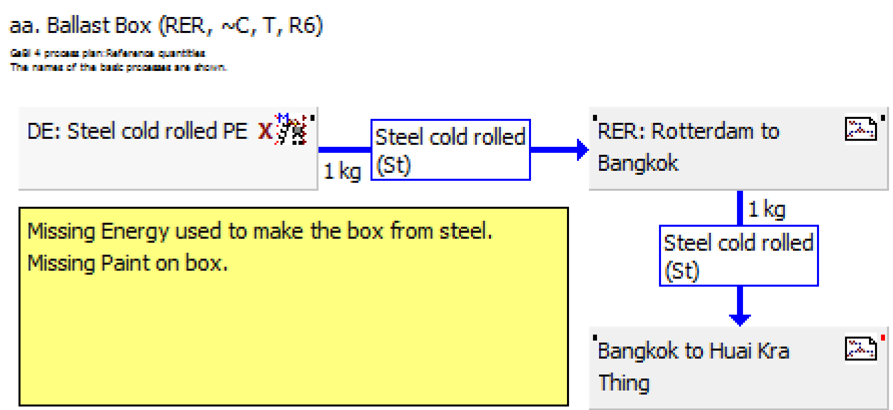


Figure D.35 Ballast Box

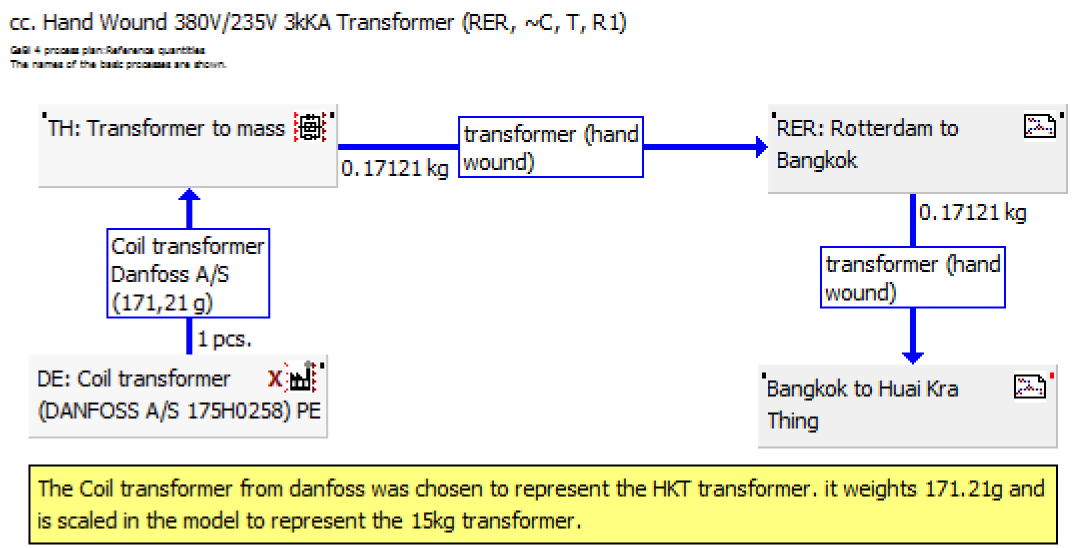


Figure D.36 Hand Wound 380V/230V Transformer

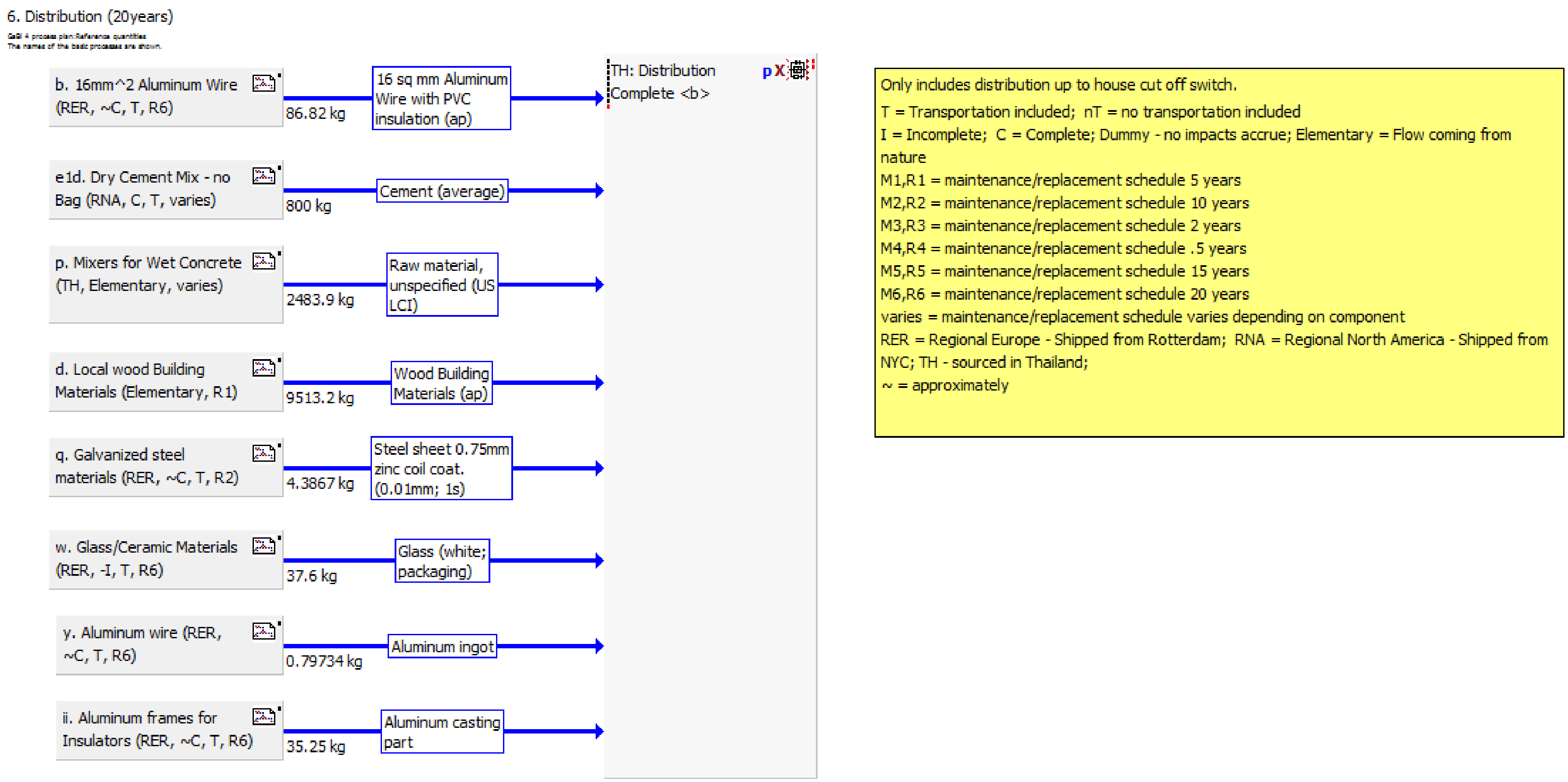


Figure D.37 Distribution

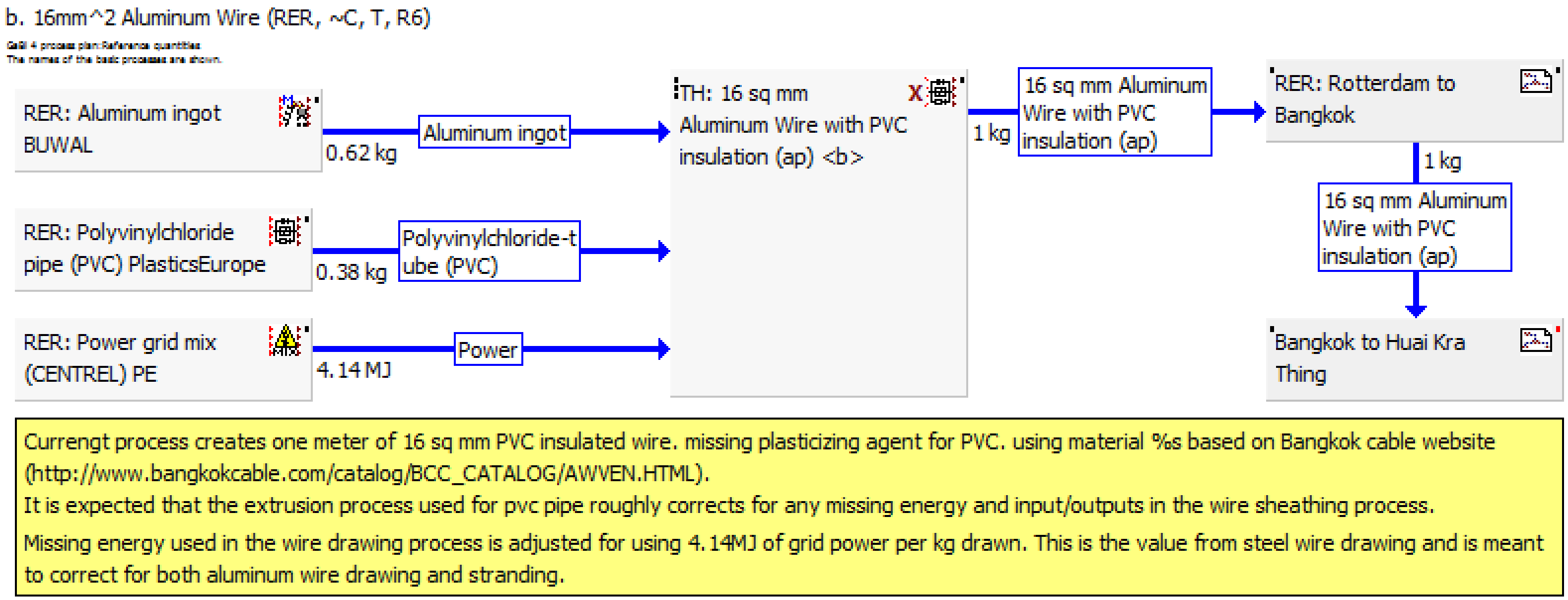


Figure D.38 16mm^2 Aluminium Wire

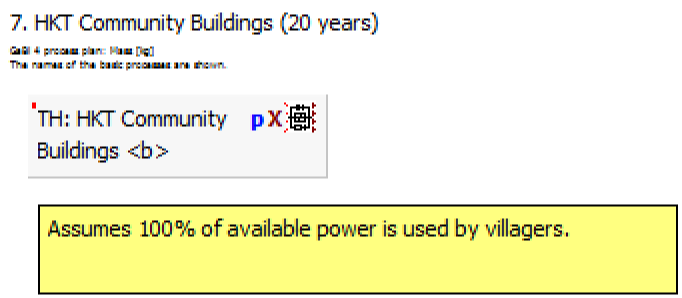


Figure D.39 HKT Community Buildings

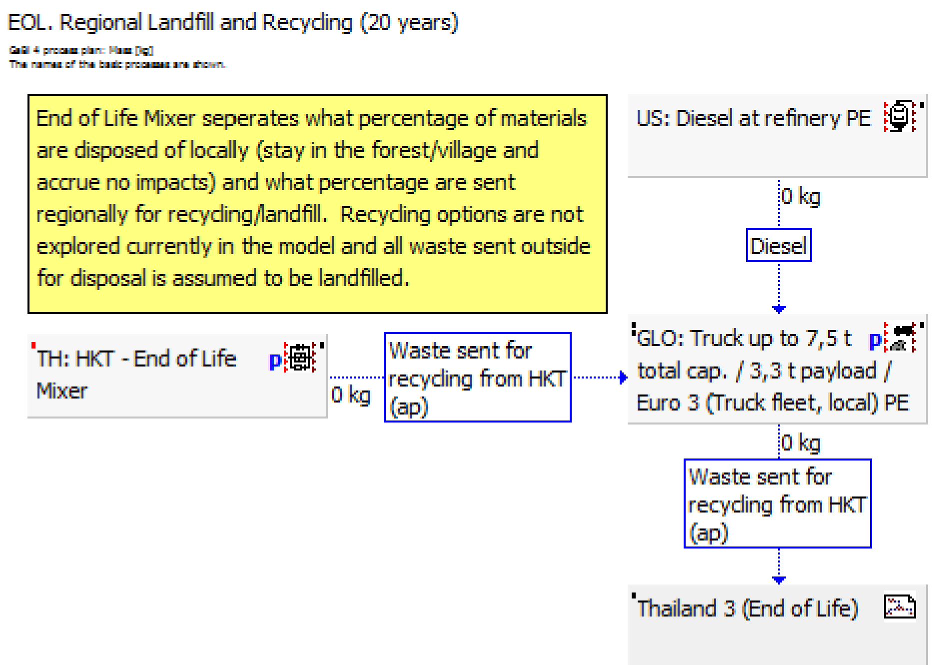
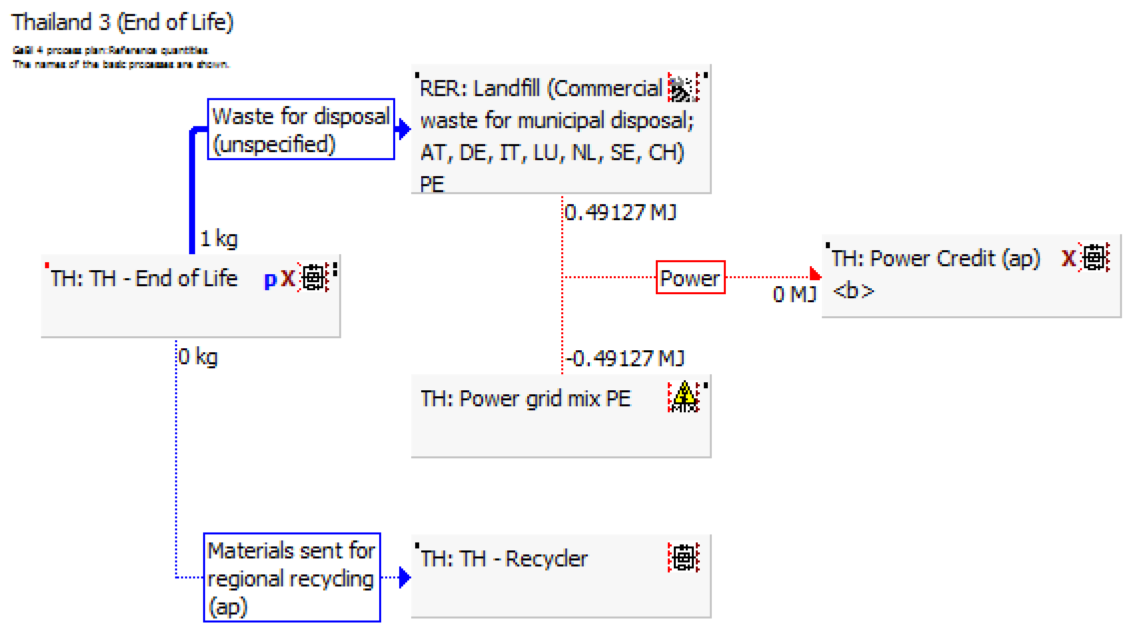


Figure D.40 End of Life



Maximum recycled is approximately 41%

Category	kg	% of total mass (materials not from HKT)
Steel	345	8%
Plastics	784	19%
Iron	301	7%
copper	70	2%
aluminum	157	4%
electronics	10	0.24%

Figure D.41 Thailand (End of Life)

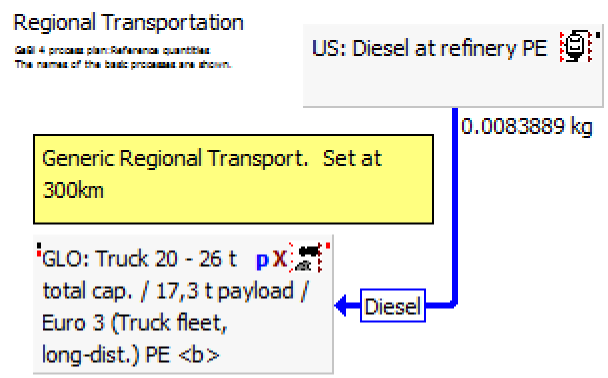


Figure D.42 Regional Transportation

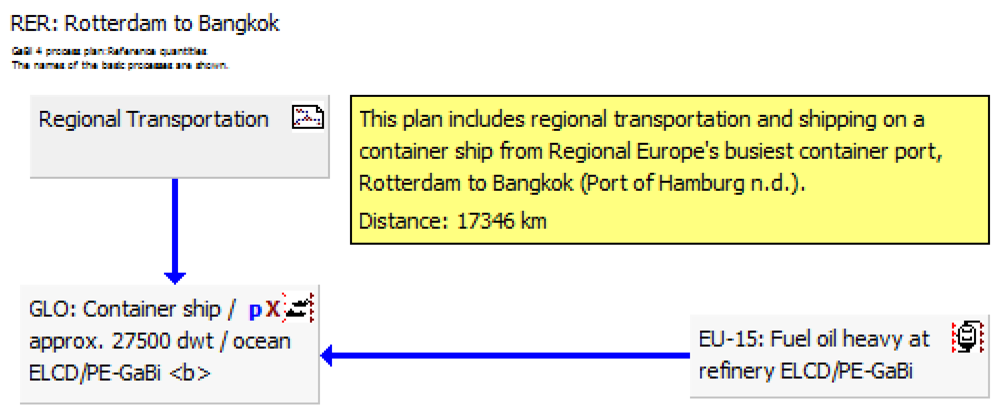


Figure D.43 RER: Rotterdam to Bangkok

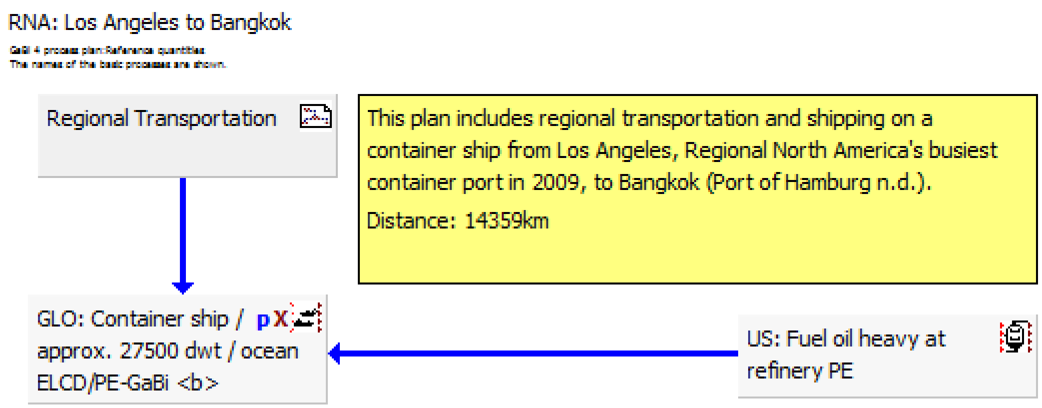


Figure D.44 RNA: Los Angeles to Bangkok

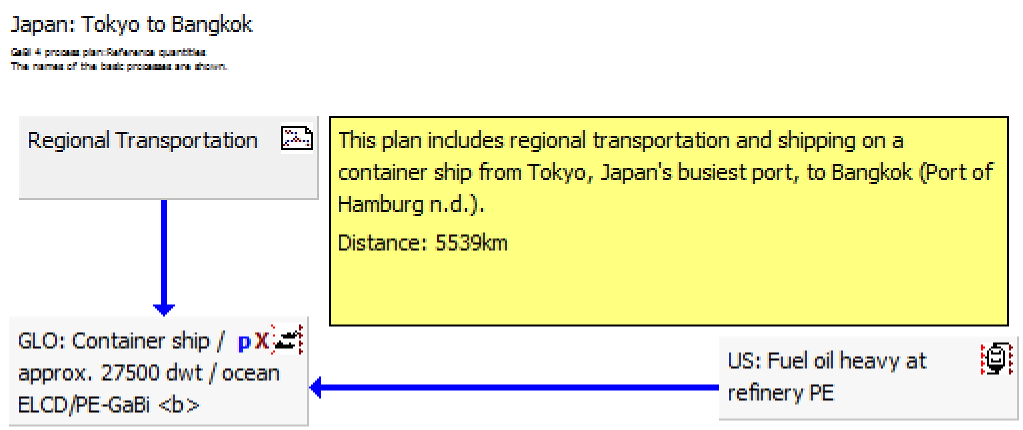


Figure D.45 Japan: Tokyo to Bangkok

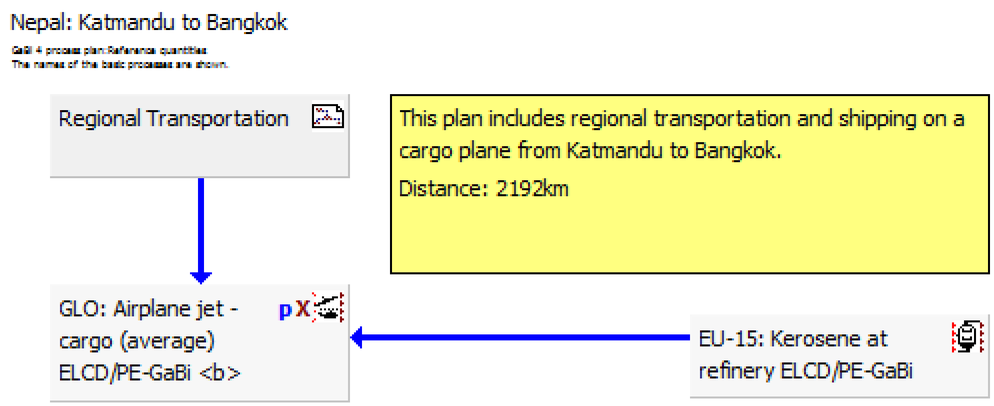


Figure D.46 Nepal: Kathmandu to Bangkok

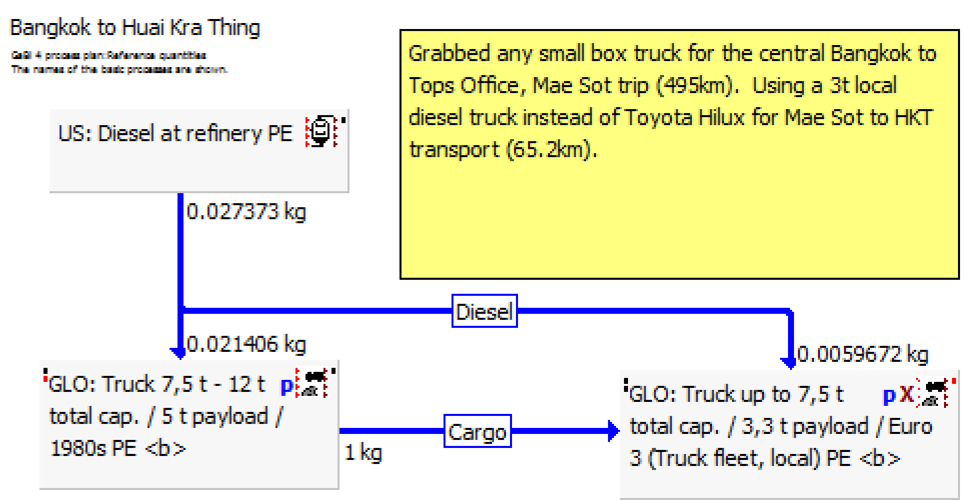


Figure D.47 Bangkok to Huai Kra Thing

Appendix E Documentation GaBi databases 2006

Metadata documentation of the process or LCI result data set: Polyvinylchloride pipe (PVC) (en)

Table of Contents: Metadata documentation of the process or LCI result information - Modelling and validation - Administrative information - Reference Flow(s)

Metadata documentation of the process or LCI result information

Key Data Set Information

Location	**RER**
Geographical representativity description	**The data set represents the country / region specific situation, focusing on the main technologies, the region specific characteristics and / or import statistics.**
Reference year	**2005**
Name	Base name **Polyvinylchloride pipe (PVC)**
Use advice for data set	**The data set represents a cradle to gate inventory. It can be used to characterise the supply chain situation of the respective commodity in a representative manner. Combination with individual unit processes using this commodity enables the generation of user-specific (product) LCAs. PlasticsEurope provides LCI datasets for several intermediates and plastics. To use these datasets in a consistent way with "GaBi Databases 2006", some adaptations in the presentation of the dataset had to be made. For details Please see "GaBi Databases Modelling Principles".**
Technical purpose of product or process	**Provision of a standard technical product according to the applied technology.**
Category Information	Top category / Sub category 1 **Systems / Unspecific parts**
General comment on data set	**The data set covers all relevant process steps / technologies over the supply chain of the represented cradle to gate inventory with a good overall data quality. The inventory is mainly based on industry data and is completed, where necessary, by secondary data.**

Copyright?	**Yes**	Owner of data set (contact data set)	**PlasticsEurope**	Additional data set documentation (source data set)	**PVC pipe extrusion** **Methodology**

Quantitative reference

Reference flow (s)	**Polyvinylchloride-tube (PVC) [Systems] - [ ] - 1 kg (Mass)**

Time representativity

Time representativity description	**Annual average**

Geographical representativity

Technological representativity

Technology description including background system	**For details please see "Additional data set documentation" from PlasticsEurope**
Flow diagramm (s) or picture(s) (sou	

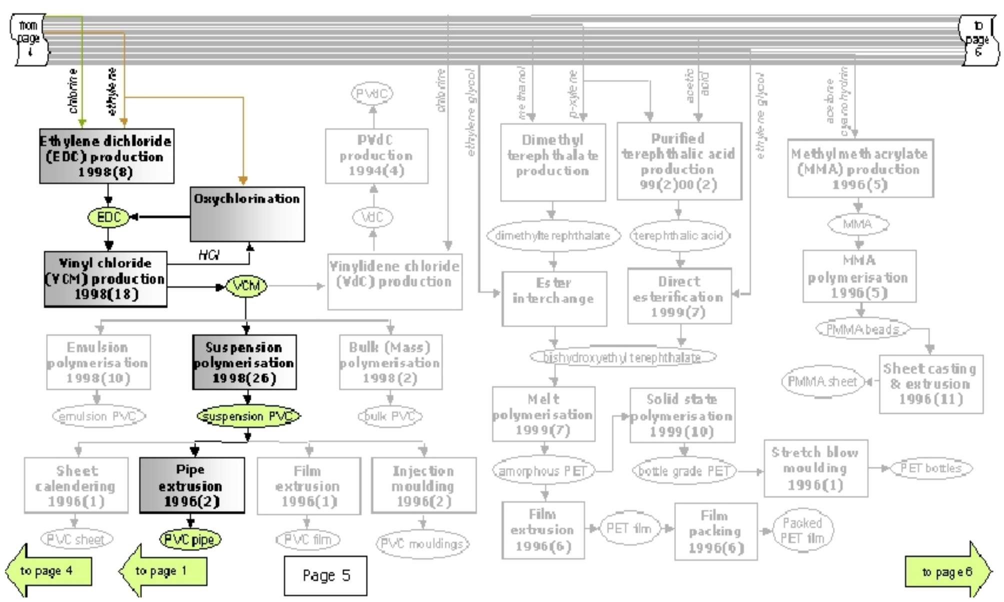


Figure E.1 Selected portion of Polyvinyl Chloride (PVC) Pipe process documentation

U.S. LCI DATABASE PROJECT

DATA MODULE REPORT

MARCH 10, 2006

PORTLAND CEMENT PRODUCTION

Module Description

This module represents the cradle-to-gate manufacture of Portland Cement based on the production weighted average of each of the four main cement plant processes (wet, long dry, dry with preheater, and dry with preheater and precalciner). Due to data confounding, a systems approach was used to present the life cycle data. For example, emissions data from the pyroprocess phase include emissions from fuel combustion along with other high temperature processes. Some energy data, such gasoline consumption are only reported for the plant as a whole, not by process step.

Portland cement is a hydraulic cement composed primarily of hydraulic calcium silicates. Hydraulic cements harden by reacting chemically with water. During this reaction, cement combines with water to form a stonelike mass, called paste. When the paste (cement and water) is added to aggregates (sand and gravel, crushed stone, or other granular materials) it binds the aggregates together to form concrete, the most widely used construction material. Although the words "cement" and "concrete" are used interchangeably in everyday usage, cement is one of the constituents of concrete. Cement is a very fine powder and concrete is a stonelike material. Cement constitutes 8 to 15 percent of concrete's total mass by weight. Using cement LCI data incorrectly as concrete LCI data is a serious error.

Scope and Boundary

The system boundary includes the four main steps in manufacturing portland cement:

(1) Quarry and crush: extracting raw material from the earth, crushing to 5-cm (2-inch) pieces, and conveying and stockpiling.

(2) Raw meal preparation: recovering materials from stockpiles, proportioning to the correct chemical composition, and grinding and blending.

(3) Pyroprocess: processing raw meal to remove water, calcining limestone and causing the mix components to react to form clinker, cooling and storing the clinker.

(4) Finish grind: reclaiming the clinker from storage, adding gypsum and grinding to a fine powder, and conveying to storage.

The system boundary also includes transporting all fuel and materials from their source to the cement plant. That is, it includes the emissions, such as from burning fuel in internal combustion engines, to transport the materials to the cement plant. It also includes combustion of fuel in the cement kiln. It generally does not include upstream profiles of producing fuel and electricity. For example, it does not include the energy and emissions associated with extracting coal or generating electricity. One exception is noted in Transportation (see Table 1 below and Source Info, page 21).

Table 1. Inclusion of Pre-combustion energy and emissions

Energy inputs by fuel type	Pre-combustion energy and emissions	Direct combustion energy and emissions
Coal	No	Yes
Gasoline	Yes	Yes
Liquefied petroleum gas	No	Yes
Middle distillates	Yes	Yes
Natural gas	No	Yes
Petroleum coke	No	Yes
Residual oil	No	Yes
Wastes	No	Yes
Electricity	No	No

Technological Representation

Data represent U.S. average technologies. The LCI data are calculated from the production weighted average of the four cement plant processes: wet, long dry, dry with pre-heater, and dry with pre-heater and pre-calciner. Although each process is quite different, they all produce the same product, that is, portland cement; and there are no significant regional differences to the geographic distribution of cement plant process and capacity.

Data Types and Sources

Data are drawn from private and public surveys (for example, from the Portland Cement Association), public U.S. statistical sources (for example, from the U.S. Geological Survey), emission factors (for example, from the U.S. Environmental Protection Agency), reports, and calculations. See module source information "tab" for specific references. This LCI data set was prepared by CTLGroup on behalf of the Portland Cement Association.

Figure E.2 Selected portion of Portland cement process documentation

Metadata documentation of the process or LCI result data set: Cast iron part (sand casting) (en)

Metadata documentation of the process or LCI result information

Key Data Set Information

Location	**DE**
Geographical representativity description	**The data set represents the country / region specific situation, focusing on the main technologies, the region specific characteristics and / or import statistics.**
Reference year	**2005**
Name	Base name **Cast iron part (sand casting)**
Use advice for data set	**The data set represents a partly terminated process which considers the most inputs as cradle to gate. The inputs of steel scrap, cast iron scrap as well as power and thermal energy are still open in order to allow the connection with specific background data sets.**
Technical purpose of product or process	**Provision of a standard technical product according to the applied technology.**
Category Information	Top category / Sub category 1 **Systems / Unspecific parts**
General comment on data set	**The data set covers all relevant process steps / technologies over the supply chain of the represented partly terminated process with a good overall data quality. The inventory is mainly based on industry data and is completed, where necessary, by secondary data.**

Copyright? **Yes** Owner of data set (contact data set) **PE International**

Quantitative reference

Reference flow(s)	**Cast iron part [Systems] - [ ] - 1 kg (Mass)**

Time representativity

Time representativity description	**Annual average**

Geographical representativity

Technological representativity

Technology description including background system	**Steel scrap, cast iron scrap and alloy components are melted in a cupola furnace and afterwards teemed into sand moulds in the foundry. The castings were sandblasted after the take-out.**

Figure E.3 Selected portion of cast iron part (sand casting) process

Metadata documentation of the process or LCI result data set: Steel cast part alloyed (en)

Metadata documentation of the process or LCI result information

Key Data Set Information

Location	**DE**
Geographical representativity description	**The data set represents the country / region specific situation, focusing on the main technologies, the region specific characteristics and / or import statistics.**
Reference year	**2005**
Name	Base name **Steel cast part alloyed**
Use advice for data set	**The data set represents a partly terminated process which considers the most inputs as cradle to gate. The input of steel scrap is still open in order to allow the connection with specific scraps.**
Technical purpose of product or process	**Provision of a standard technical product according to the applied technology.**
Category Information	Top category / Sub category 1 **Systems / Unspecific parts**
General comment on data set	**The data set covers all relevant process steps / technologies over the supply chain of the represented partly terminated process with a good overall data quality. The inventory is mainly based on industry data and is completed, where necessary, by secondary data.**
	Copyright? **Yes** Owner of data set (contact data set) **PE International**

Quantitative reference

Reference flow(s)	**Steel casting part [Systems] - [ ] - 1 kg (Mass)**

Time representativity

Time representativity description	**Annual average**

Geographical representativity

Technological representativity

Technology description including background system	**Steel scrap and alloy components are melted in an electric furnace and afterwards moulded in sand moulds. After the take-out a heat treatment and deburring of the work piece are following.** **The background system is addressed as follows:**

Figure E.4 Selected portion of steel cast part alloyed process

Metadata documentation of the process or LCI result data set: Stainless steel cold roll (en)

Metadata documentation of the process or LCI result information

Key Data Set Information

Location	**DE**
Geographical representativity description	**The data set represents the country / region specific situation, focusing on the main technologies, the region specific characteristics and / or import statistics.**
Reference year	**2004**
Name	Base name **Stainless steel cold roll**
Use advice for data set	**The data set represents a cradle to gate inventory. It can be used to characterise the supply chain situation of the respective commodity in a representative manner. Combination with individual unit processes using this commodity enables the generation of user-specific (product) LCAs.**
Technical purpose of product or process	**Provision of a standard technical product according to the applied technology.**
Category Information	Top category / Sub category 1 **Materials / Metals and semimetals**
General comment on data set	**The data set covers all relevant process steps / technologies over the supply chain of the represented cradle to gate inventory with a good overall data quality. The inventory is mainly based on industry data and is completed, where necessary, by secondary data.**

Copyright? **Yes** Owner of data set (contact data set) **PE International**

Quantitative reference

Reference flow(s)	**Stainless steel (cold rolled) [Materials] - [Metals and semimetals] - 1 kg (Mass)**

Time representativity

Time representativity description	**Annual average**

Geographical representativity

Technological representativity

Technology description including background system	**The data set represents the stainless steel production in Germany based on the main production steps which take place within an electric steelmaking plant. The main process step hereby is the melting of stainless steel scrap in the electric arc furnace (EAF), thus the consumed energy is mainly electric power.** **The major feed stock for the EAF is stainless steel scrap, which may comprise of scrap**

Figure E.5 Selected portion of stainless steel cold roll process

Metadata documentation of the process or LCI result data set: Copper mix (99,999% from electrolysis) (en)

Metadata documentation of the process or LCI result information

Key Data Set Information

Location	**DE**
Geographical representativity description	**The data set represents the country / region specific situation, focusing on the main technologies, the region specific characteristics and / or import statistics.**
Reference year	**2002**
Name	Base name **Copper mix (99,999% from electrolysis)**
Use advice for data set	**The data set represents a cradle to gate inventory. It can be used to characterise the supply chain situation of the respective commodity in a representative manner. Combination with individual unit processes using this commodity enables the generation of user-specific (product) LCAs.**
Technical purpose of product or process	**Provision of a standard technical product according to the applied technology.**
Category Information	Top category / Sub category 1 **Materials / Metals and semimetals**
General comment on data set	**The data set covers all relevant process steps / technologies over the supply chain of the represented cradle to gate inventory with a good overall data quality. The inventory is mainly based on industry data and is completed, where necessary, by secondary data.**

Copyright? **Yes** Owner of data set (contact data set) **PE International**

Quantitative reference

Reference flow (s)	**Copper (99.999%; electrolyte copper) [Materials] - [Metals and semimetals] - 1 kg (Mass)**

Time representativity

Time representativity description	**Annual average**

Geographical representativity

Technological representativity

Technology description including background system	**This data set includes the copper mix of Germany. The copper ore is already processed in different mines in Northern America, Central and South America as well as Australia, Africa and Asia to the copper concentrate which approximately contains about 30% copper. The copper feed undergoes a converter process and is refined by electrolysis, producing copper electrodes. It is then cast either into continuous wire or billets. For the production of strips cakes are molten and brought into the new form by rolling, pickling, and annealing. Shaped wires for special purposes are produced by sawing, hot pressing, pickling and annealing of copper billets.** **Country specific energy and transportation were considered in this inventory.** **The background system is addressed as follows:** **Electricity, Thermal energy: The electricity (and thermal energy as by-product) used is modelled according to the individual country-specific situation. The country-specific modelling is achieved on multiple levels. Firstly the individual power plants in service are modelled according to the current national grid. This includes net losses and imported electricity. Second, the national emission and efficiency standards of the power plants are modelled. Third, the country-specific fuel supply (share of resources used, by import and / or domestic supply) including the country-specific properties (e.g. element and energy contents) are accounted for. Fourth, the import, transport, mining and exploration processes for the energy carrier supply chain are modelled according to the specific situation of each power-producing country. The different mining and exploration techniques (emissions and efficiencies) in the different exploration countries are accounted for according to current**

Figure E.6 Selected portion of copper mix (99,999% from electrolysis) process

Metadata documentation of the process or LCI result data set: Aluminium die-cast part (en)

Table of Contents: Metadata documentation of the process or LCI result information - Modelling and validation - Administrative information - Reference Flow(s)

Metadata documentation of the process or LCI result information

Key Data Set Information

Location	**DE**
Geographical representativity description	**The data set represents the country / region specific situation, focusing on the main technologies, the region specific characteristics and / or import statistics.**
Reference year	**2005**
Name	Base name **Aluminium die-cast part**
Use advice for data set	**The data set represents a gate to gate unit process. It can be used to characterise related processes in LCAs.**
Technical purpose of product or process	**Provision of a standard technical product according to the applied technology.**
Category Information	Top category / Sub category 1 **Systems / Unspecific parts**
General comment on data set	**The data set covers all relevant input and output flows of the represented gate to gate unit process with a good overall data quality. The inventory is mainly based on industry data and is completed, where necessary, by secondary data.**

Copyright? **Yes** Owner of data set (contact data set) **PE International**

Quantitative reference

Reference flow(s)	**Aluminum part [Systems] - [ ] - 1 kg (Mass)**

Time representativity

Time representativity description	**Annual average**

Geographical representativity

Technological representativity

Technology description including background system	**Aluminium (normally recasted Aluminium) is warmed up to its smelting temperature in a glory-hole and further on feeded into the pressure casting machine. The cavity void is filled up with metal after closing the two tool parts. Cooling water lowers the temperature of the part depending on its geometry and qualities and the tool can be opened. The part is taken from the cavity and the feed head and burr is removed.**

Modelling and validation

Figure E.7 Selected portion of aluminium die-cast part process

Metadata documentation of the process or LCI result data set: Coil transformer (DANFOSS A/S 175H0258) (en)

Table of Contents: Metadata documentation of the process or LCI result information - Modelling and validation - Administrative information - Reference Flow(s)

Metadata documentation of the process or LCI result information

Key Data Set Information

Location	**DE**
Geographical representativity description	**The data set represents the country / region specific situation, focusing on the main technologies, the region specific characteristics and / or import statistics.**
Reference year	**2002**
Name	Base name **Coil transformer (DANFOSS A/S 175H0258)**
Use advice for data set	**The data set represents a cradle to gate inventory. It can be used to characterise the supply chain situation of the respective commodity in a representative manner. Combination with individual unit processes using this commodity enables the generation of user-specific (product) LCAs.**
Technical purpose of product or process	**Provision of a standard technical product according to the applied technology.**
Category Information	Top category / Sub category 1 **Systems / Electrics and Electronics**
General comment on data set	**The data set covers all relevant process steps / technologies over the supply chain of the represented cradle to gate inventory with a good overall data quality. The inventory is mainly based on industry data and is completed, where necessary, by secondary data.**

Copyright?	**Yes**	Owner of data set (contact data set)	**PE International**	Additional data set documentation (source data set)	**Material mix: Components (specific)**

Quantitative reference

Reference flow (s)	**Coil transformer Danfoss A/S (171,21 g) [Systems] - [Electrics and electronics] - 1 piece (Number of pieces)**

Time representativity

Time representativity description	**Annual average**

Geographical representativity

Technological representativity

Technology	**Procedural Steps: The most important groups of housed, electronic components are**

Figure E.8 Selected portion of Coil Transformer

Metadata documentation of the process or LCI result data set: Printed wired board FR4 (4l; 2s; AuNi finishing) (en)

Table of Contents: Metadata documentation of the process or LCI result information - Modelling and validation - Administrative information - Reference Flow(s)

Metadata documentation of the process or LCI result information

Key Data Set Information

Location	**RER**
Geographical representativity description	**The data set represents the country / region specific situation, focusing on the main technologies, the region specific characteristics and / or import statistics.**
Reference year	**2002**
Name	Base name **Printed wired board FR4 (4l; 2s; AuNi finishing)**
Use advice for data set	**The data set represents a cradle to gate inventory. It can be used to characterise the supply chain situation of the respective commodity in a representative manner. Combination with individual unit processes using this commodity enables the generation of user-specific (product) LCAs.**
Technical purpose of product or process	**Provision of a standard technical product according to the applied technology.**
Category Information	Top category / Sub category 1 **Systems / Electrics and Electronics**
General comment on data set	**The data set covers all relevant process steps / technologies over the supply chain of the represented cradle to gate inventory with a good overall data quality. The inventory is mainly based on industry data and is completed, where necessary, by secondary data.**

Copyright?	Owner of data set (contact data set)	Additional data set documentation (source data set)
Yes	PE International	Materiax mix: PWB

Quantitative reference

Reference flow (s)	**PWB (Mass) [Systems] - [Electrics and electronics] - 0.1 kg (Mass)** **PWB (Area) [Systems] - [Electrics and electronics] - 0.0225 m2 (Area)**

Time representativity

Time representativity description	**Annual average**

Geographical representativity

Technological representativity

Technology description including background system	**Procedural Steps: PWB (Printed Wiring Board) means one or multi layered substrates where already the copper trace layout per layer is applied. Base of the process routes is the manufacture of FR4 substrates. The main important process steps are: mechanical treatment of copper clad epoxy-glass fibre layer (e.g. drilling, stamping), surface cleaning (e.g. degreasing, staining, etching), structuring of traces (e.g. screen printing, photo printing with exposure), etching of PWB (e.g. chemical, electrolyte-chemical), through plating (e.g. chemical, electrolytic), surface treatment (e.g. tin/lead, gold over nickel) and coating (e.g. solder resist, protective lacquer, label printing). The processes are applied per layer particularly also iterative. At multi layer PWBs the respective layers are pressed after finishing each trace layout and following through plated (drilling, etching, copper deposition, surface treatment of through holes). The considered multi layer types relate from one layered single sided PWBs up to six layered double sided PWBs. In mass production up to ten layered PWBs are manufactured, technically practical are also up to 20 layered multi layers.** **Boundary Conditions: The model of the FR4 manufacture contains the consumption of base materials, most relevant auxiliaries and energy consumption as well as most important emissions from processing. The base materials are scaled according to PWB mass, the auxiliaries and the energy consumption according to the PWB size. The latter also is differentiated according to inner layers and outer layers. The various types of FR4 are set to a fixed ratio of mass to size (differs per number of layers, see spreadsheet). Thus the black box processes are scalable either by mass or size, the ratio thereby is still fixed. The most relevant flows are captured, the data quality is good considering the set ration of mass to size and number of layers, the data relate to average applied process steps.** **The background system is addressed as follows:** **Electricity, Thermal energy: The electricity (and thermal energy as by-product) used is modelled according to the individual country-specific situation. The country-specific modelling is achieved on multiple levels. Firstly the individual power plants in service are modelled according to the current national grid. This includes net losses and imported electricity. Second, the national emission and efficiency standards of the power plants are modelled. Third, the country-specific fuel supply (share of resources used, by import and / or domestic supply) including the country-specific properties (e.g. element and energy contents) are accounted for. Fourth, the import, transport, mining and exploration processes for the energy carrier supply chain are modelled according to the specific situation of each power-producing country. The different mining and exploration techniques (emissions and efficiencies) in the different exploration countries are accounted for according to current engineering knowledge and information.**
Included and corresponding data sets (process or LCI result data set)	Thermal energy from natural gas [DE] Power grid mix [UCTE] Soda (Na2CO3) [DE]

Figure E.9 Selected portion of printed wire board process documentation

Metadata documentation of the process or LCI result data set: Power grid mix (en)

Table of Contents: Metadata documentation of the process or LCI result information - Modelling and validation - Administrative information - Reference Flow(s)

Metadata documentation of the process or LCI result information

Key Data Set Information

Location	**TH**
Geographical representativity description	**The data set represents the country / region specific situation, focusing on the main technologies, the region specific characteristics and / or import statistics.**
Reference year	**2002**
Name	Base name **Power grid mix**
Use advice for data set	**The data set represents a cradle to gate inventory. It can be used to characterise the supply chain situation of the respective commodity in a representative manner. Combination with individual unit processes using this commodity enables the generation of user-specific (product) LCAs.**
Technical purpose of product or process	**Provision of a standard technical product according to the applied technology.**
Category Information	Top category / Sub category 1 **Energy carrier / Electricity**
General comment on data set	**The data set covers all relevant process steps / technologies with a good overall data quality. The inventory is based on measured operating data taken from national statistics, literature data and / or calculated via energy carrier composition in combination with (literature-based) combustion models.**
	Copyright? **Yes** Owner of data set (contact data set) **PE International**

Quantitative reference

Reference flow (s)	**Power [Energy carriers] - [Electricity] - 3.6 MJ (Lower calorific value)**

Time representativity

Time representativity description	**Annual average**

Geographical representativity

Technological representativity

Technology description including background system

The national / regional electricity consumption mix is provided by multiple energy carriers. The country / region specific mix is shown in the pie chart "Electricity Mix". The electricity is either produced in energy carrier specific power plants and / or energy carrier specific heat and power plants (CHP). The country / region-specific fuel supply (share of resources used, by import and / or domestic supply) including the country / region-specific energy carrier properties (e.g. element and energy contents) are accounted for. Furthermore country / region specific technology standards of power plants regarding efficiency, firing technology, flue-gas desulphurisation, NOx removal and dedusting are considered. The national / regional electricity consumption mix is modelled as shown in the flow diagram "Modelling of Power Consumption Mix". It includes imported electricity, net losses and the own use by energy producers. The electricity (and in some countries thermal energy as by-product) is modelled according to the individual country / region-specific situation, too.

The data set considers the whole supply chain of the fuels from exploration over extraction and preparation to transport of fuels to the power plants.

The background system is addressed as follows:

Electricity, Thermal energy: The electricity (and thermal energy as by-product) used is modelled according to the individual country-specific situation. The country-specific modelling is achieved on multiple levels. Firstly the individual power plants in service are modelled according to the current national grid. This includes net losses and imported electricity. Second, the national emission and efficiency standards of the power plants are modelled. Third, the country-specific fuel supply (share of resources used, by import and / or domestic supply) including the country-specific properties (e.g. element and energy contents) are accounted for. Fourth, the import, transport, mining and exploration processes for the energy carrier supply chain are modelled according to the specific situation of each power-producing country. The different mining and exploration techniques (emissions and efficiencies) in the different exploration countries are accounted for according to current engineering knowledge and information.

Steam: The steam supply is modelled according to the individual country-specific situation with regard to the technology efficiencies and energy carriers used. Efficiencies range from 84% to 94% in relation to the representative energy carrier (gas, oil, coal). Coal, crude oil and natural gas used for the generation of steam are modelled according to the specific import situation (see electricity).

Transports: All relevant and known transport processes used are included. Overseas transports including rail and truck transport to and from major ports for imported bulk resources are included. Furthermore all relevant and known pipeline and / or tanker transport of gases and oil imports are included.

Energy carriers: Coal, crude oil, natural gas and uranium are modelled according to the specific import situation (see electricity).

Refinery products: Diesel, gasoline, technical gases, fuel oils, basic oils and residues such as bitumen are modelled via a country-specific, refinery parameterized model. The refinery model represents the current national standard in refinery techniques (e.g. emission level, internal energy consumption,...) as well as the individual country-specific product output spectrum, which can be quite different from country to country. Hence the refinery products used show the individual country-specific use of resources. The supply of crude oil is modelled, again, according to the country-specific crude oil situation with the respective properties of the resources.

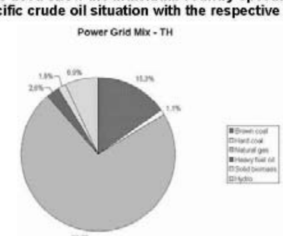
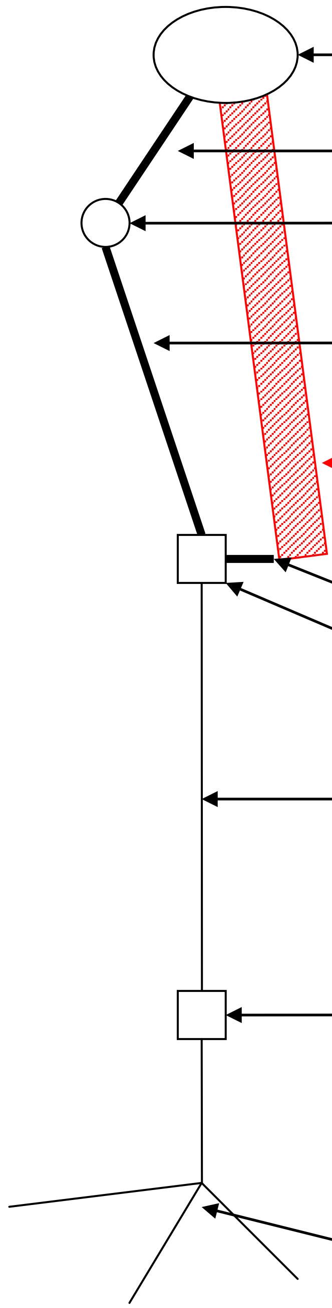


Figure E.10 Selected portion of Thai power grid process

Appendix F: Land Use Change Footprint calculation for HKT Hydro Installation (not to scale, nor directly representational)



Backup flow behind weir: width x length = ~ 5m x 5m = 25m^2

Canal: length x width = ~ 25m x .254m = 6.35m^2

Settling Tank: pi * radius tank squared = ~ Pi * .4m * .4m = .5m^2

Penstock: length x width = ~ 172m * .127m = 21.84m^2

River: ~width river * ~length river impacted by reduced flow = ~ 2m * ~235m = 470m^2

Outflow: length * width = ~ 4m * .152m + .5m2 = 1.112m^2

Powerhouse: width x length = ~ 2m x 2m = 4m^2

Transmission Line: pi * radius hole for power pole = ~ .35m * 35m * pi * 40 = 15.394m^2 (this only considers power pole footprint)

Control House: width x length = ~ 2m x 2m = 4m^2

Distribution Lines: pi * radius hole for power pole = ~ .35m * 35m * pi * 40 = 15.394m^2 (this only considers power pole footprint)

Total Land Occupied = ~ **93.59m^2**

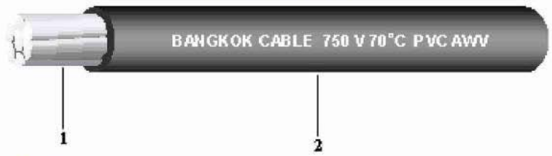
Potential land use change ~ **470m^2** #

Note that river length and width used to arrive at this value are estimates.

Appendix G: Bangkok cable specifications for 25mm² and 16mm² aluminium cable (Bangkok Cable 2005)

750 V 70°C AWV

TIS 293-2541, TABLE 2



Construction :

1. Conductor : Compact round stranded hard-drawn aluminium wires
2. Insulation : Polyvinyl chloride (PVC), Black color

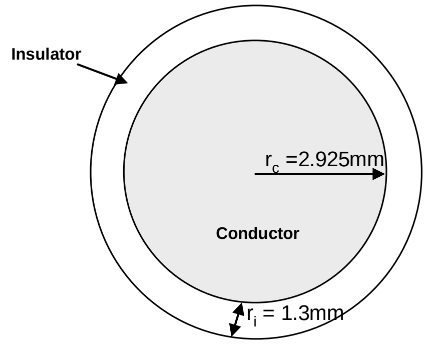
Application :

Used for low voltage overhead distribution.

Nominal cross sectional area sq.mm	No. of wire No.	Conductor diameter mm	Thickness of insulation mm	Overall diameter approx mm	Maximum Conductor resistance at 20 °C ohm/ km	Minimum Insulation resistance at 70 °C M ohm/ km	Breaking strength N	Current rating in air A	Cable weight (Approx.) kg/ km	Standard Length m
10	6	3.68	1.1	6.4	3.08	0.0076	1768	58	54	500/D
16	6	4.65	1.1	7.4	1.91	0.0063	2734	77	77	500/D
25	6	5.85	1.3	9.1	1.20	0.0060	4120	100	118	500/D

Appendix H: Mass input calculations for Aluminium Cable

Aluminum Cable - 25mm^2 cross section



Area Conductor = Pi * r_c^2 = 3.1416 * (.002925)^2 = .0000269m^2

Volume Conductor over 1m length = Area Conductor * 1m = .0000269m^3

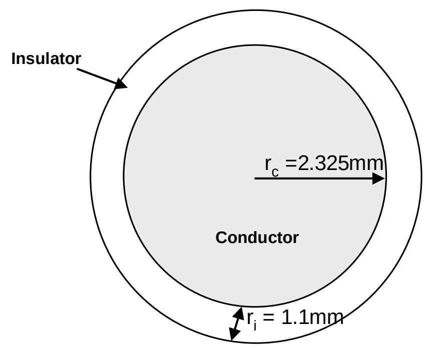
Mass Conductor over 1m length = Volume Conductor * Density Aluminum = .0000269m^3 * 2700kg/m^3 = **.0726kg**

Area Insulation = [Pi * (r_c+r_i)^2] – Area Conductor = [3.1416*(.004225)^2] - .0000269 = .0000292m^2

Volume Insulator over 1m length = Area Insulator * 1m = .0000292m^3

Mass Insulator over 1m length = Volume Insulator * Density PVC = .0000292m^3 * 1400kg/m^3 = **.0409kg**

Aluminum Cable - 16mm^2 cross section



Area Conductor = Pi * r_c^2 = 3.1416 * (.002325)^2 = .00001698m^2

Volume Conductor over 1m length = Area Conductor * 1m = .00001698m^3

Mass Conductor over 1m length = Volume Conductor * Density Aluminum = .00001698m^3 * 2700kg/m^3 = **.0459kg**

Area Insulation = [Pi * (r_c+r_i)^2] – Area Conductor = [3.1416*(.003425)^2] - .00001698 = .00001987m^2

Volume Insulator over 1m length = Area Insulator * 1m = .00001987m^3

Mass Insulator over 1m length = Volume Insulator * Density PVC = .00001987m^3 * 1400kg/m^3 = **.0278kg**

Appendix I: IGC (IGC version) Parts list from Hummingbird manual

(Portegijs 2000)

For standard 2 dump load IGC version:	
Component	**quantity needed**
Resistors	
1 W resistors:	
100R/1W	1
4k7/1W	1
1% metal film resistors:	
24k3/0.25W/1% (or use 22k + 2k2)	1
100k/1% (or use matching set of ordinary resistors)	4
332k/1%	4
Ordinary 5% resistors:	
150R/0.25W/5%	5
1k	5
1k5	1
2k2	10
3k3	1
5k6	6
10k	13
12k	1
15k	3
18k	1
22k	2
27k	2
33k	1
47k	6
56k	1
100k	5
220k	5
1M	3
Trimmers, 10 mm, lying version:	
250R	1
2k5	1
5k	1
10k	1
25k	4
100k	1
NTC resistor:	
100k	1
Capacitors:	
Leads 5 mm apart:	
10n/100V `Wima'	1
47n/100V	5
100n/63V	9
470n/63V	4
Leads 7.5 mm apart:	
47n/250V	1
`class Y' noise suppression capacitor:	
100n/250VAC	1
`Elco' capacitors, radial leads:	
47u 16V	12
2200 u 35V	3
Semiconductors:	
1N4148 signal diode	26
250V/1.5A bridge rectifier	1
24V/1.3W zener diode	1
LED red, 3 mm	5
LED yellow	1
LED green	2
BC237B transistor	3
BD139 transistor	1
BRX49 thyristor	1
78L15 stabilized voltage supply	1
LM324N opamps	4
LM329DZ reference voltage	1

Component	quantity needed
Miscellaneous	
14 pin IC connector	4
32mA `slow' fuse 5 x 20 mm	1
18V/4.5VA transformer	1
DIN 41617 connector, 13 pin, on PCB	1
2-sided epoxy PCB material with photo-sensitive layer	1
pins for connecting component- with copper-side tracks	40
measuring points, can be made from excess leads or copper wire	14
Power circuit	
TIC263M triac	2
S07K420 varistor, 420Veff, 1.2kA	2
S20K460 varistor, 460Veff, 8kA	1
S20K625 varistor, 625Veff, 6.5kA	1
core for noise suppression coil (26 x 14.5 x 20)	2
2.5mm^2 cable, m	1.5
heat sink, for 2 dump load version.	1
aluminum plates, 50x50x4 mm	2
Resin core solder, 100 g	0.2
relay, 2 x 30 A	1
Silicone insulation sheet, 200x200mm*	0.125
Silicone paste `for glass'*	0.1
connector rail, 35 mm `omega'	0.1
end support	1
string clamps, 4 mm^2	8
grounding clamps	4
(or: connector block 30 A)	0
housing, class IP55 or better	1
cable pass-through	4
nut for cable pass-through	4
perspex cover	1
Label explaining LED's	1
Chemicals for printing PCB	0
Soldering flux and corrosion protection spray (`SK10')	0.1
Drill bit, 0.8 mm	2
Drill bit, 1.1 mm (or 1.0 or 1.2mm)	1
Protective spray for PCB	0.1
Thermal Bonding Compound	0.5
fuse holder, 5 x 20 mm vertical	1
DIN 41617 connector, 13 pin, on cable	1
signal cable, 10 wire	0.3
M4x10 sunken head screws + nuts	2
4mm^2 twin cable (both black), m	0.2
Frequency effect to overvoltage:	
10k resistor	9
220k	1
100n/63V capacitor	1
47u Elco, 16V, radial leads	1
1N4148 signal diode	1
LM324N opamp	1
extra for frequency effect:	**7**
IGC version:	
2k21/0.25W/1% metal film resistor (or use matching pair of ordinary resistors)	2
12k1/1% (or matching pair)	2
24k3/1% (or use 22k + 2k2)	1
332k/1%	3
82R/0.25W/5% ordinary resistor	1
5k6	-1
10k	3
27k	1
33k	1
56k	1
220k	-1
2k5 trimmer	1
100n/63V capacitor	1
680n/63V	1
4u7/35 V Elco, radial leads	1
1N4148 signal diode	3
LM324N opamps	1
S07K420 varistor, 420Veff, 1.2kA	-2
S07K275 varistor, 275Veff, 1.2kA	2

Appendix J: HKT System Efficiency and Loss Calculations (Davis 2009; Greacen 2006; BGET 2006b)

Consideration	Formula	Result	Unit
Primary power to Electrical power			
Theoretical power available at 10 L/s for HKT (no losses)	= Density Water (1000 kg/m^3) * Head (34m) from BGET (2006b) * Water Flow (.01m^3/s) from Greacen (2006) * Gravity (9.80665 m/s^2)	3334	W
Power Available from Turbine at 10 L/s after install	= Figure from Greacen (2006) report	1600	W
Efficiency of Penstock, Turbine and Motor	= Power Out of turbine (1600W) / Theoretical Power Available (3334W)	47.99%	
Transmission Line Efficiency			
Distance of Transmission Wire Run	= suvrey length of 25sqmm cable (BGET 2006b)	1200	m
Resistance for 1m of 25mm sq area Aluminum Wire	= ~.348 ohm/1000foot (Davis 2009) [25sqmm is 49338circ mils] * 1000 foot/304.8m	0.0011	ohm/m
Calculated Voltage Drop for 4.21 A over x-mis of 25mmsq cable	= Transmission Length (1200m) * Resistance for 1m of 25mm sq area Aluminum Wire (~.00106ohm) * Current at Turbine Output (4.21A)	5.77	V
Calculated efficiency for Transmission Line	= 100% - Total Transmission Line Losses	98.48%	
Power Available at Control House before Transformer	= (Voltage out at Turbine - Voltage Drop) * Current in Transmission Line	1576	W
Transmission Line Losses	= Power Out of transmission line at CH (1576W) / Power IN to transmission line at PH (1600W)	1.52%	
Conversion and Control Efficiency			
3kW Transformer Efficiency (380V/235V) loaded at 1.6kW (53.33%)	= Estimate [Interpolationt from Department of Energy (2007) for a 3kW single phase inverter loaded at 35% gives 97.34%]. This estimate assumes higher losses due to operation under high ambient temperatures along with hand wound Thai manufacture of HKT transformer.	95%	
ELC and Electronics Efficiency	= Estimate. No conversion is occuring. Only solid state switching.	99%	
Calcualted efficiency for Conversion and Control Equipment	= 3kW Transformer Efficiency * ELC and Electronics Efficiency	94.05%	
Power available at CH after Conversion and Control Equipment	= Power Available at Control House before Transformer (1576W) * Efficiency for Conversion and Control Equipment	1482	W
Average Distribution Efficiency			
Longest Distribtuion Run	= distribution to Roman Catholic Church (BGET 2006b)	363	m
Shortest Distribution Run	= dsitrubution to village school (BGET 2006b)	10	m
Resistance for 1m of 16mm sq area Aluminum Wire	= ~.544 ohm/1000foot (Davis 2009) [16sqmm is 31576 circ mils] * 1000 foot/304.8m	0.0018	ohm/m
Voltage on Secondary Winding of Transformer	= 235V from Greacen (2006)	235	V
Maximum current available from distribution to village at CH	= Power available at CH after Conversion and Control Equipment / Secondary winding voltage on transformer	6.3062	A
Calculated Voltage Drop for maximum current available on longest distribution run	= Longest Distribution Run (363m) * Resistance for 1m of 16mm sq area Aluminum Wire (~.0018ohm) * Max Current available at CH (6.3062A)	4.09	V
Calculated Voltage Drop for maximum current available on shortest distribution run	= Shortest Distribution Run (10m) * Resistance for 1m of 16mm sq area Aluminum Wire (~.0018ohm) * Max Current available at CH (6.3062A)	0.11	V
Maximum Power Available at end of longest Distribution Run	= (Voltage at CH - Voltage Drop longest run) * Max current in Distribution Line	1456	W
Maximum Power Available at end of shortest Distribution Run	= (Voltage at CH - Voltage Drop shortest run) * Max current in Distribution Line	1481	W
Maximum Distribution Losses	= Power Out at end of Longest Distribtuion Run (1456W) / Power IN distribution line at CH (1482W)	1.7%	
Minimum Distribution Losses	= Power Out at end of shortest distribution run (1481W) / Power IN distribution line at CH (1482W)	0.05%	
Average Efficiency for Distribution	= 100% - (Max Distribution losses - Min Distribution Losses)/2	99.15%	
Overall Efficiency Factor to be applied to Power	= Transmission Line Efficiency (98.5%) * Conversion and	**92%**	
Average Power available at connection to	= Power Available from Turbine at 10 L/s after install (1600W) *	**1469**	**W**

Appendix K: GaBi Modelling Parameters

CementBagMass	50	kg per cement bag
ChEff	0.9405	Efficiency of electronics in control house
DaysYear	365.25	Days in a year
DistEff	0.99155	Average efficiency in distribution line (Average of largest loss and smallest loss)
DumptUse	0	average amount of available power being sent to the dump load
Flow_1600Wh	36	m^3 per hour to produce 1.6kWh of energy at turbine
HoursDay	24	Hours in a day
Lifetime_A	20	Expected lifetime of Weir (major component A)
Lifetime_B	20	Expected Lifetime of penstock (major component B)
Lifetime_C	5	year for lifespan of pump/motor (major component C)
Lifetime_D	20	years of lifetime on transmission wire (major component D)
Lifetime_E	5	years of ELC and transformer lifetime (major component E)
Lifetime_F	20	years of lifetime on distribution (major component F)
Lifetime_G	20	Community Building Connection Expectancy
Maintenance_Schedule1	5	years on maintenance schedule 1
Maintenance_Schedule2	10	years on maintenance schedule 2
Maintenance_Schedule3	2	years on mainteance schedule 3
Maintenance_Schedule4	0.5	years on maintenance schedule 4
Maintenance_Schedule5	15	years on maintenance schedule 5
Maintenance_Schedule6	20	years on maintenance schedule 6
MassPenstock_1m	2.9912	kg per 1 meter of schedule C four inch penstock
MixersCement	3.1049	kg mixers for one kg of cement
MJperkWh	3.6	Energy Conversion
OperatingFactor	0.85	Annual percentage of year that the system is in operation
PenstockLength	172	Length of Penstock in Meters
PowerTurbine	1.6	kW of power from turbine at 10l/s
StudyLength	20	Project study span in years
TransEff	0.98482	Efficiency of transmission line
Waste	4144.1	kg of waste to be disposed of. Does not include local materials.
WaterMass	1000	kg per m^3 H20

Appendix L: Summary of data analysis from two periods of scheme logging

(BGET 2006a; BGET 2007)

System Performance observed at Control House Using a Data Logger		
Data Logging Period	10:00 March 16 to 10:00 April 25, 2006	
Days during logging period	40	days
Logging Frequency	15	minutes
Calibrated voltage Bounds used to filter logged data	150 < 270	Vac
Expected Energy Available at CH from System (1576W x 24h x 40 days)	1,512,960	kWh
Logged energy Available to village at CH	213,304	kWh
Logged Energy Consumed by Village (not including school)	40,847	kWh
Logged energy available vs expected energy available (%)	14%	
Logged Energy Consumed vs Logged Energy Available (%)	19%	
Data Logging Period	12:48 February 9 to 17:26 February 21, 2007	
Days during logging period	11.2	days
Logging Frequency	2	minutes
Calibrated voltage bounds used to filter logged data	150 < 270	Vac
Expected Energy Available at CH from System (1576W x 24h x 11.2 days)	423,629	kWh
Logged energy Available to village at CH	71,405	kWh
Logged Energy Consumed by Village (not including school)	37,523	kWh
Logged energy available vs expected energy available (%)	17%	
Logged Energy Consumed vs Logged Energy Available (%)	53%	

Appendix M: GaBi 4 plans for the diesel generator system

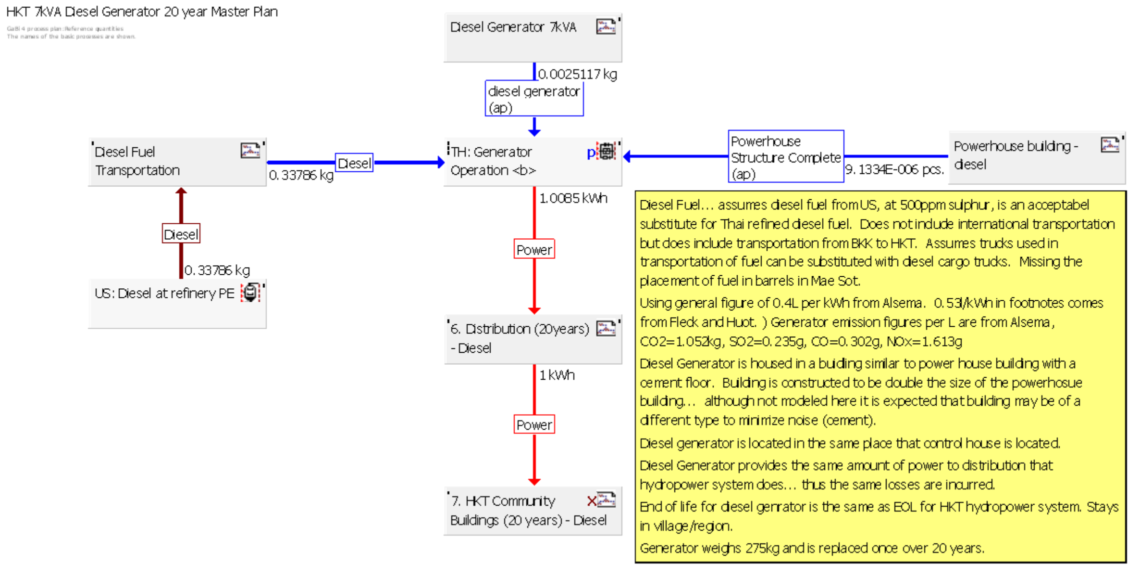


Figure M.1 HKT 3kVA Diesel Generator Master Plan

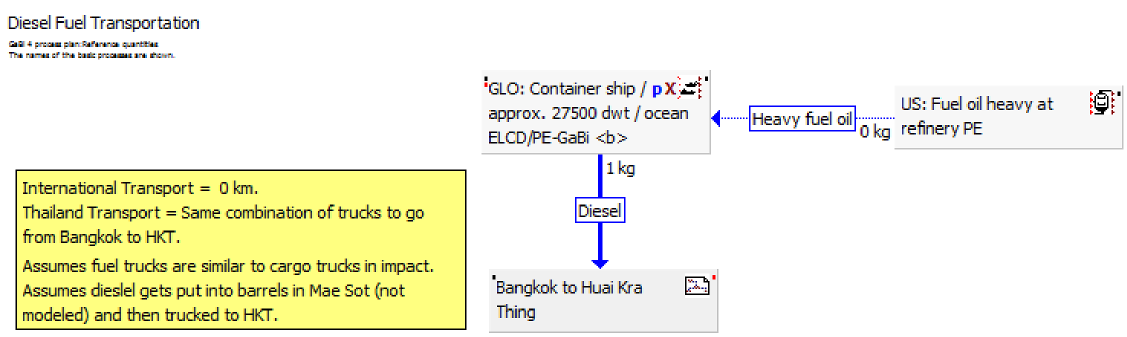


Figure M.2 Diesel Fuel Transportation

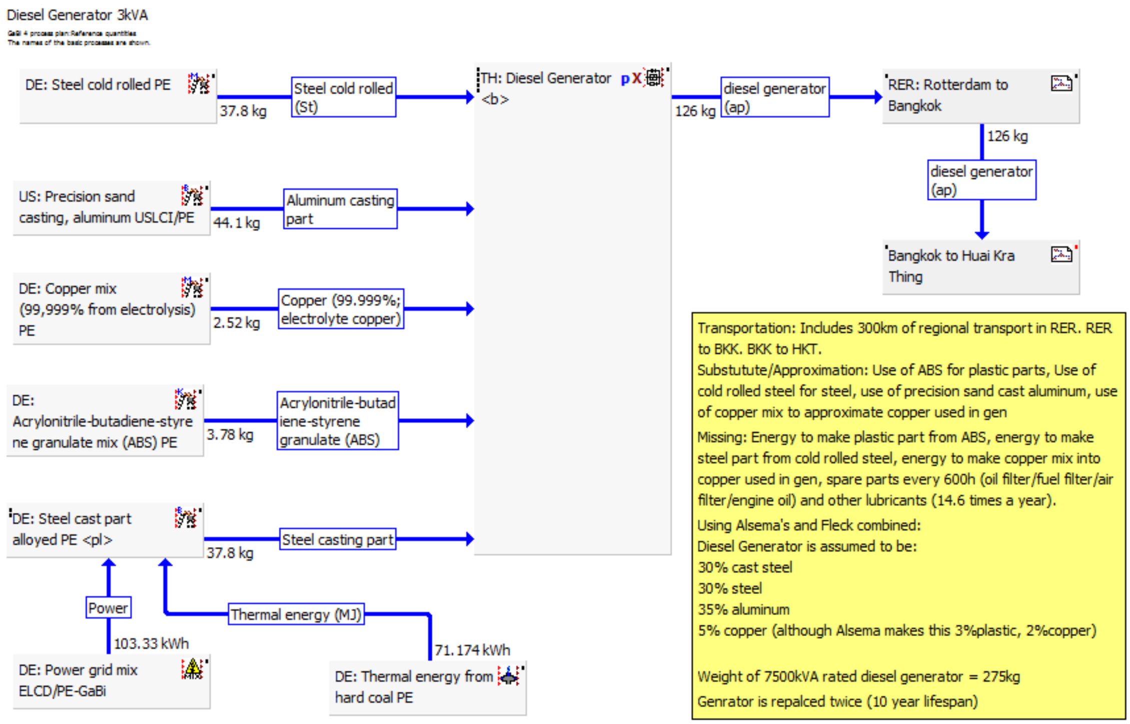


Figure M.3 Diesel Generator

Appendix N: GaBi 4 plans for HKT connection to the Thai Power Grid

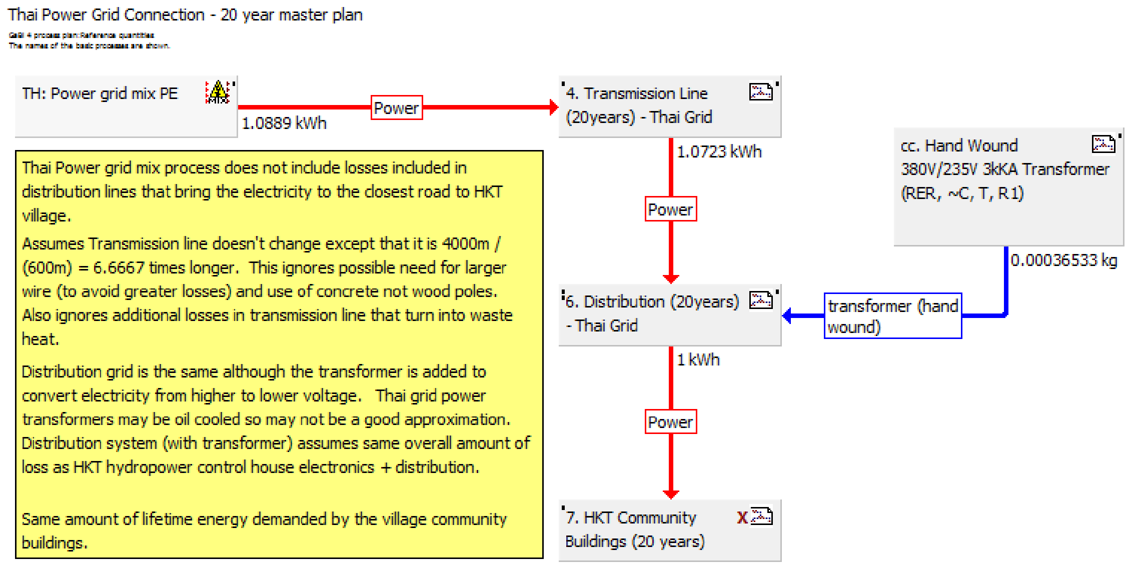


Figure N.1 Thai Power Grid Connection - 20 year master plan

Appendix O: Survey of the key characteristics of recent literature covering hydropower LCAs (Vattenfall 2008a; Vattenfall 2008b; Gagnon et al. 2002; Rule et al. 2009; IEA 2002; Hondo 2005; Pehnt 2006)

Study	Standard(s)	Method/Software	Reported LCIA Results [a]	Functional Unit	Hydro Scheme(s) Data and Location(s)	Hydro Technology	Capacity (MW)	Lifespan scheme (years)	Included *^	Excluded *^
Hondo et al. 2005	Not stated in English	LCA combination: process and I/O analysis	GHG	1 kWh net, at plant	Japan 100%	Run of River w/ small reservoir	10	30 (Sensitivty: -20, +70)	C, T, OM	D, R, GC, TD, B, S, ?L
Vattenfall 2008	EPD, ISO 14025, ISO 14040, ISO 14044	Full LCA according to EPD standards	GHG,AP,EP, ODP, POCP, PE, LU	1 kWh net at plant / TD losses	Sweden 93%, Finland 7%	Reservoir 93%, Run-River 7%	2.4 - 1001	60 machinery, 100 Civil works	C, T, OM, GC, TD, (D of TD), S, ?L	R, (D of plant)
Pehnt 2006	Not stated	Streamlined process LCA / Umberto software package	GHG, AP, EP, PE	1 kWh, at plant	~Germany, not explicity stated	Run of River	0.3	Not provided	C, T, OM, R, D, ?GC	?TD, ?B, ?S, ?L
					~Germany, not explicity stated	Run of River	3.1	Not provided	C, T, OM, R, D, ?GC	?TD, ?B, ?S, ?L
Rule et al. 2009	ISO 14044	Simplified process LCA / SigmaPro 7	GHG, PE	1 KWh generated	New Zealnd	Reservoir	432	100 Dam, all others scaled to 100	~C, T, OM, GC, R, ~D	TD, (D of Dam), B, S, L
Gagnon et al. 2002	Not stated, various	Summary of LCAs from last decade	generic GHG, SO2, NOx, PE, LU	1 kWh	North American and European conditions	Reservoir	n/a	~100, although some use 50	Not stated, various	Not stated, various
						Run of River	n/a	~100, although some use 50	Not stated, various	Not stated, various
IEA 2002	~ISO 14040 [b]	Summary of LCAs	LU, PE, POCP, Others	1 kWh plant output	UCPTE[c], Sweden, Norway, Japan	Reservoir and Run of River	n/a	Scaled to 100	Check each study	Check each study

[a] GHG=Greenhouse Gasses, AP=Acidification Potential, EP=Eutrophication Potential, ODP=Ozone Depletion Potential, POCP=Photochemical ozone creation potential, PE=Primary Energy, LU=Land Use, SO2=Sulpher dioxide, NOx=Nitrogen Oxides

[b] "It is also doubtful if there currently are any complete LCI on electricity generation that complies with ISO 14040, because the standard was established only recently." (IEA 2002)

[c] Union for the Coordination of Production and Transmission of Electricity (IEA 2002)

* C=creation, T=transport, OM=Operation and Maintenance, D=Decomissioning, R=Recycling, GC=Plant to Grid Connection, TD=Transmission and Distribution after GC, B=Biomass decomposition in reservoir, S=Switchyard gear, L=Lubricants

^ When author did not state directly what was included and excluded, an educated guess was made from wording in literature. In this case, a ? Appears before the category. ~ signifies a partial consideration.

Appendix P: Table 4 … recent literature

(Vattenfall 2008a; Vatte… 2009; IEA 2002; Hondo 2005; Pehnt 2006)

Study	Hydro Technology
Hondo et al. 2005	Run of River w/ small reservoir
Vattenfall 2008	Reservoir 93%, Run-River 7%
Pehnt 2006	Run of River
	Run of River
Rule et al. 2009	Reservoir
Gagnon et al. 2002	Reservoir
	Run of River
IEA 2002	Reservoir and Run of River

Appendix Q: Primary Energy Demand (kJ/kWh) equations and sample calculations for HKT and surveyed literature

Huai Kra Thing

Primary Energy Demand (kJ/kWh)

= Primary Energy Demand * conversion coefficient to convert kWh to kJ

= .150 * 3600 kJ/kWh

= 540 kJ/kWh

Vattenfall 2008

Primary Energy Demand (kJ/kWh)

= (Renewable fuel resource use + Fossil energy resources + Electricity use in the power station) * conversion coefficient to convert kWh to kJ

= (.0082 kWh/kWh + .0000095 kWh/kWh + .0033 kWh/kWh) * 3600 kJ/kWh

= 41.4 kJ/KWh

Pehnt 2006

Primary Energy Demand (kJ/kWh)

= Cumulative Energy Demand (CED)[29] for non-renewable fuel resources

= .14 MJ/kWh * 1000 kJ/MJ 9 (for Hydropower 300kW$_{el}$)

= 140 kJ/kWh

Rule et al. 2009

Primary Energy Demand (kJ/kWh)

= Embodied Energy[30]

= **55 kJ/kWh**

Gagnon et al. 2002

Primary Energy Demand (kJ/kWh)

= (1 / Energy Payback[31]) * conversion coefficient to convert kWh to kJ

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[29] "CED, cumulative (non-renewable) energy demand; co-combustion in hard coal power plant; reciprocating engine, gasified wood in Otto engine; SRF, short rotation forestry." (Pehnt 2006, 60).

[30] "Embodied energy includes all primary energy used by a product or process, including fuel and electricity" (Rule et al. 2009).

= (1 / 40kWh/kWh) * 3600 kJ/kWh

= 90 kJ/kWh (for Run of the river maximum value)

IEA 2002

Primary Energy Demand (kJ/kWh)

= (1 / Energy Ratio[32]) * conversion coefficient to convert kWh to kJ

= (1 / 50kWh/kWh) * 3600 kJ/kWh

= 72 kJ/kWh

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[31] "For each power generation system, the ''energy payback'' is the ratio of energy produced during its normal life span, divided by the energy required to build, maintain and fuel the generation equipment" (Gagnon et al. 2002, 1275).

[32] "The energy analysis ratio is an index used to indicate how many times the energy of power generation is greater than the energy consumption for construction and operation of the equipment" (IEA 2002, 164).

Appendix R: Results, reported per kWh of electricity produced by each system, from LCA studies of rural electrification systems.

		Gmünder et al (2010)				Alsema (2000)		
Characterization and Impact Category or Indicator	Unit/kWh	Jatropha	Jatropha Optimized	Diesel	Diesel Optimized	SHS 2	BCS - Grid	Diesel 6kVA
CML2001- Dec. 07 ADP	g Sb - Equiv.							
CML2001- Dec. 07 AP	g SO2 - Equiv.					3.900	14.700	16.50
CML2001- Dec. 07 EP	g Phosphate - Equiv.					0.217	0.947	2.40
CML2001- Dec. 07 GWP 100 years	g CO2 - Equiv.	268	133	1800	1180.00	583	2290	1270
CML2001- Dec. 07 ODP, steady state	g R11 - Equiv.					2.10E-04	7.29E-04	2.28E-03
CML2001- Dec. 07 POCP	g Ethene - Equiv					0.356	0.841	1.27
Primary Energy Demand	kWh	13.95	4.10	9.00	5.10	3.17	11.25	4.78